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GEOLOGICAL MAGAZINE

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"Flattening" in Dalradian Quartz-Schist north of Stonehaven, Kincardineshire

By T. C. PHEMISTER and D. H. WILLIAMSON

ABSTRACT

In the schistose grits of the Dalradian Series north of Stonehaven there is clear evidence of the deformation of the rock by shearing of the original quartz grains along planes roughly diagonal to the "flattening", which here coincides generally with the schistosity of the quartz-schist, the final product of the metamorphism. As this corresponds essentially to the case studied by Schmidt and others, an examination of the rock fabric is made having in mind the mechanism suggested by Schmidt, and more fully elaborated by Anderson, to connect up crystal orientation with deformation. The results of the study do not indicate that the simple model of equal spheres, each with its set of glide planes, and all in cubical packing, is in any way adequate to explain the petrography of this quartz-schist and it is suggested that any theory that makes a purely mechanical reaction of the quartz grains to the deforming forces the dominant factor in the production of a new texture is at variance with the facts since there is clear evidence of the continued solution and crystallization of quartz throughout the whole of the metamorphic period.

INTRODUCTION

ONE of the greatest difficulties facing the student of structural petrology is that, while he may measure at will the orientation of grains in deformed rocks, he has little or no information regarding the relations between the crystal orientations and the movements and forces which are presumed to have produced them. Indeed it is open to question whether, for example, in the case of quartz any such connection exists at all. Most of the attempts to interpret the "fabric" in terms of the movements have been concerned only with mechanics and of these one of the most precise is that advanced by Schmidt (1932, 190–3) to explain what has been termed "flattening" in schists and allied rocks. His analysis is particularly interesting as it goes beyond the movement to embrace also the system of stresses which is considered to have brought about the deformation. The great simplifying assumption that he makes in this connection is to regard the rock as composed of a system of equal spheres each with its set of

glide planes, and as this analysis is well known to all workers there is no need to do more than summarize its essentials here. These equal spheres, arranged on a cubic pattern, are thought to be subjected to shearing forces along the planes of maximum shearing stress and, through the frictional forces brought into play by the shear at the surfaces of the grains, the latter are subjected to equal and opposed couples about an axis at right angles to the plane of deformation. The efficiency of these couples in rotating the grains is lessened in measure as their forces are spent in gliding within the grains themselves. Hence, whereas spheres without internal glide planes would rotate continuously due to adjustments within the rock as a whole, grains possessing these planes of movement are brought ultimately into definite orientations from which any tendency to rotation one way or another by the frictional couples is offset by dissipation of the forces of the couple in gliding.

Anderson (1948) has given a more penetrating analysis of the mechanics of the shears themselves. The strains he regards as simple shears and bases his treatment on the well-known theorem that any simple shear may be resolved into a pure strain and a rotation, these two elements bearing a definite relation to one another and to the amount of the shear. The distortion of the medium is everywhere homogeneous and both the plane and the direction of the shear remain constant throughout. Each element is thus subjected simultaneously to a pure strain and to a bodily rotation. To connect this deformation with the final texture of the rock Anderson applies the same basic assumption regarding its structure as does Schmidt, namely that it is made up of equal spheres in cubical packing. On such a structure the results of the simple shear are twofold: first, the spherical grains rotate relative to one another and, secondly, the element itself undergoes a bodily rotation. The relative rotation subjects each sphere to a frictional force exerted by its neighbours in the plane of deformation and, if all of the grains were stress-isotropic, it is held that on the average the frictional couples would balance one another out and there would be no resultant rotation. Hence, in this case, the bodily rotation alone of the element would give a continuous rotation to the grains, a rotation which would keep pace with the deformation. If, however, the grains possessed sets of glide planes, the rotating effect would be more complex and the simplest relations are provided by the case where a grain possessing a single set of glide planes is in contact in the deformation plane with isotropic grains. Here the balance between the two frictional couples acting on this central grain is affected by the possibility of internal gliding in the grain itself and, whenever the energy of one couple is expended on this deformation, its power to rotate the grain is correspondingly diminished with the

result that the other couple effects a definite rotation. In certain orientations of the glide planes this rotation will be added to that due to the bodily rotation of the element while in others the two rotations will be in opposition. Hence there is a tendency for this central grain ultimately to remain in an orientation such that the trace of the intersection of its set of glide planes with the deformation plane lies within a certain maximum angle to the direction of the shear. These simple rules are held to govern the more complex case where all the grains possess glide planes. In the general case these glide planes will not be, prior to the shear, at right angles to the plane of the deformation and so the final effect will be to bring the poles of the glide planes into the plane normal to the deformation plane. Depending on the facility with which gliding can be initiated there will be a region of 20 to 30 degrees from the normal to the deformation plane in which poles of the glide planes will be absent since the glide in the crystal becomes too oblique to the direction of shear to be effective. On the other hand, there should be a strong tendency towards a maximum at the intersection of this zone with the deformation plane.

This pattern of deformation is applied, amongst other minerals, to quartz, accepting the glide planes and directions of glide that have been suggested by various writers from time to time. With the glide direction [0001] and the glide plane $(10\bar{1}0)$, the optic axes would be expected to give a maximum along the direction of the shear. On the other hand, with a direction of glide at right-angles to this and with the glide plane $(10\bar{1}1)$ or $(10\bar{1}0)$ there would be a girdle of optic axes at right-angles to the direction of the shear.

This is but a brief summary of Anderson's careful discussion of the problem and the reader must consult his paper for the full details.

Do either of these theories in any way represent the processes that obtain during regional metamorphism ? As the authors themselves well realize, they present some marked inconsistencies with the petrography of the crystalline schists. A fundamental difficulty and one common to all such purely mechanical theories is expressed by Anderson when, drawing his analogy between ideal canal flow and rock deformation, he points out that, whereas the viscosity of water is 0·01, that of a rock near the surface is of the order of 10^{22}. In spite of this enormous difference in this fundamental property he considers that it is probable that the rules which govern the production of simple shear in the two substances are similar. It is true, as Hubbert (1937) has shown, that were we making a model of the deformation this difference would not be so formidable as the figures suggest but the reason would be that the time necessary for the production of the deformation in the two cases would be correspondingly great. It is here that the question must always be asked: " if geological time is

the measure of the rate of rock movement can one be sure that the reactions will be simply physical? Though mechanical factors must certainly operate, will not recrystallization be the dominating factor in the formation of textures as it is in the production of new minerals?" The perfect development of the minerals that we find in the schists in contrast to the sheared, distorted, and granulated material characteristic of the great fault and thrust zones makes it difficult to accept the view that the textures of these crystalline rocks have been produced mainly by mechanical reactions to stress. However, this is a much wider topic than the present study which is concerned with the detail of the reaction to stress in quartz rocks and therefore with the basic assumption of both Schmidt and Anderson that a rock, a sandstone say, undergoing regional metamorphism can be represented by an assemblage of equal quartz spheres rotating relative to one another, and as a whole, during the deformation. Anderson himself, one takes it, is not too happy about the analogy for he states succinctly one of the main objections by drawing attention to the fact that in a schist the different constituents fit one another's outlines like the halves of a tally. For this condition to continue there must be constant growth in some parts of the outline with retrocession in others. Despite this, however, he maintains that the inner parts of the grains rotate while their shells recrystallize and it is these inner parts that are considered to form the cubical arrangement of equal spheres. Accepting this model, is it consistent with the simple treatment of canal flow which is adopted? Can such a structure be regarded as capable of homogeneous deformation? Certainly the rock element pictured, with its cross-section of cubically packed spheres, does not satisfy the essential condition of homogeneity in its structure, and one wonders if under the stress system indicated it would deform as described, for its deformation history would depend so much on the original arrangement and on the relative perfection of the surfaces of the balls. If the spheres were originally in either cubical or hexagonal closest-packing it is difficult to see how any movement could take place without crushing of the grains at their contacts and a transfer of the debris to the interstices. If, on the other hand, the arrangement were of a more open type, the relative movements would depend on the initial configuration of the system when the stresses were applied. But even discounting these structural difficulties one is faced with a more formidable obstacle when one tries to assess how in practice the nice balance demanded by theory between the frictional couples could be attained. Presumably the rock is under high hydrostatic pressure while the shearing factor is operative and this pressure is bound to be localized as directed pressures at the grain boundaries. While it might be possible to put forward a theoretical set of conditions under which these surface forces would be identical

it is obvious that they could not be assumed to hold in actual rocks where the forces at the grain contacts would certainly vary throughout both in magnitude and direction. Furthermore the frictional force must depend on the nature of the surfaces themselves and these surfaces in their turn will be affected by any gliding which takes place within the grain. It is difficult to see therefore how, with all these imponderable factors entering, that nice balance of the opposing couples essential to the dynamics of the rotating process could ever be attained.

Yet, despite all these objections, this is the only consistent presentation of a possible sequence of events which would bring about an orientated texture on purely mechanical reaction of the rock components, and for this reason it has always seemed worth while trying to find an example in the rocks themselves where the evidence of the shearing forces was convincing and the accompanying textures were sufficiently clear and distinct to be studied microscopically. Such a case was found in the course of work on the Dalradian rocks north of Stonehaven and the results of a petrofabric study of this material will now be described.

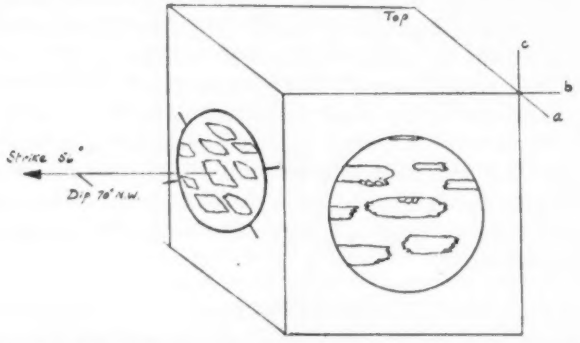
Petrography

In this occurrence of the Dalradian rocks a prominent member of the series is a grit of variable granularity but usually containing numerous thin, argillaceous partings. Practically all of these grits show evidence of " flattening ", that is, the grains originally equidimensional, have become flat ellipsoids, and the rock shows evidence of shearing along planes very roughly diagonal to this flattening. Many of these beds are now in the form of schists and, where this is so, the plane of flattening coincides with the schistosity. One of these typical schists in which the original quartz grains are still clearly recognizable occurs near the south end of Perthumie Bay, about 200 yards south of the three post-metamorphic porphyry intrusions. Although all the rocks in the Bay have a constant strike (56° east of north) and dip (70° north-west), and there is no visible folding, a study of the graded bedding, etc., has proved that the strata have been thrown into a series of tight anticlines and synclines with axial planes dipping steeply to the north-west.

The metamorphic setting of the schists is the biotite zone as defined by Barrow (1893), although recent studies by Williamson (1953) have shown that the details of the zoning show certain complexities. Thus, while a hundred yards south of the quartz-schist, the typical argillaceous member carries biotite, this mineral rapidly disappears northwards and the typical assemblage becomes chloritoid-muscovite-quartz. Biotite does not reappear until staurolite becomes the typical metamorphic mineral and thus the argillaceous rocks in the immediate

vicinity of the quartz-schist we are considering are chloritoid-muscovite schists.

This quartz-schist consists of small flattened quartz grains set in a micaceous ground-mass, the plane of flattening coinciding with the visible schistosity. Elsewhere, where folding can be seen, the strike of this schistosity coincides with the fold axis, B. A thin section cut at right-angles to this strike and parallel to the dip showed that the large detrital quartz grains appeared roughly elliptical in cross-section,



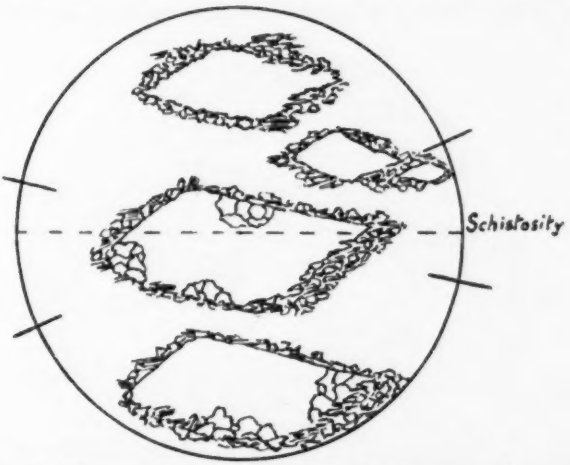
TEXT-FIG. 1.—Block diagram to illustrate the dimensional orientation of detrital quartz grains with respect to the fabric axes.

but it was clear also that this form was really due in many cases to the imperfect development of rhombs, the sides of which made relatively low angles with the plane of schistosity. On the other hand, a section at right-angles to the dip and parallel to the strike indicated that the detrital quartz grains, though still elongated parallel to the schistosity, here showed roughly rectangular cross-sections, the narrow ends being ragged or rounded. It would thus appear that the grains have been flattened in the *ab* fabric plane and have a roughly circular outline in that plane, i.e. in a section parallel to both strike and dip. (See Text-fig. 1.)

Where the cross-sections of the detrital quartz grains were clearly rhombic, measurements were made of the inclination of their sides to the schistosity and it was found that they formed fairly constant angles on either side of this plane, though one set makes a somewhat smaller angle than the other as demonstrated in Text-fig. 2. The longest axis of these grains is thus not exactly coincident with the direction of the schistosity. It seems reasonable to assume that lines drawn parallel to the sides of these grains correspond to *s*-planes along which shearing has taken place and this is borne out by the fact that the larger detrital grains are frequently bordered by recrystallized quartz of extremely fine grain as shown in Text-figs. 2 and 3. This

recrystallization has also produced new crystals inside the boundary of the original grain as indicated in the drawings.

In this rock there is certainly no evidence of a physical rotation of the grains. This is interesting to note since the metamorphic grade of these rocks is not high and one might have expected signs of this purely mechanical reaction to the shear. The adjacent argillaceous beds contain abundant sericitic mica which is still of very fine grain



TEXT-FIG. 2.—Diagramatic sketch to show the presence of recrystallized quartz with white mica bordering, and at times occurring inside, the detrital grains. The largest quartz crystals are of the order of one millimetre in length.

and in the quartz-schist itself the quartz has not yet developed the mosaic pattern of interlocking grains more characteristic of the highly metamorphosed siliceous rocks. The low metamorphic grade makes it possible to distinguish the clearly detrital grains, which presumably still preserve their original random orientations.

If the fine-grained recrystallized quartz bordering these detrital grains has arisen as suggested by granulation or shearing along the two intersecting planes defined by the present grain boundaries, it should, on the views summarized in the introduction, bear some imprint of the movement. If deformation can induce a preferred orientation of the quartz lattice then the effect should be most obvious in material which is recrystallizing in direct response to stresses imposed on it. Thus for this quartz-schist the recrystallized quartz might well be expected to have a fabric reflecting the effects of the deformation whereas the detrital grains should lack any preferred orientation connected with the movements. To examine these relations four thin sections were cut, three perpendicular to the strike and one parallel to it.

Petrofabric Study

The sections were made somewhat thicker than normal and the diagrams of the quartz orientation were prepared in the usual way. A 1 per cent counter at one centimetre intervals was used but in order to locate more accurately the contours and possible maxima whose positions did not coincide with intersections of the centimetre paper, extra positions were also counted. The horizontal or strike line is shown on the diagrams by a line with an arrowhead at one end, the

Text-fig. 3.—This shows the rhombic or elliptical shape of most of the detrital quartz grains. Sections are cut perpendicular to strike and parallel to dip. AB represents the trace of the schistosity.

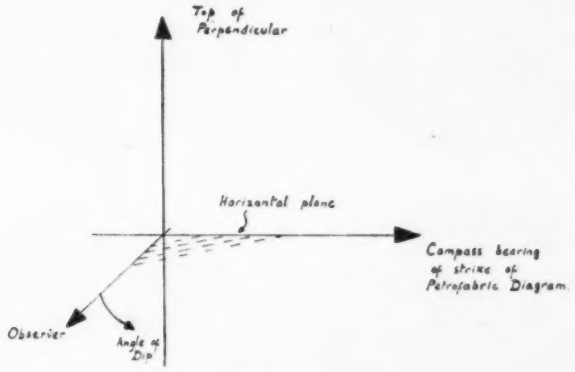
figure near the arrow indicating the orientation of the strike of the petrofabric diagram referred to a 360° compass rose. The correct orientation of a diagram may be obtained by reference to the three directions shown in Text-fig. 4. These three directions—

(1) the strike of the petrofabric diagram defined by the 360° reading,
(2) the perpendicular pointing upwards,
(3) the line of sight from the specimen to the observer,

define a right-handed set of cartesian axes. The dip is given by the positive angle measured from the horizontal. The arrowhead in all diagrams will thus always be to the right of the observer and, since most of the sections have been cut perpendicular to the strike, the diagrams will be vertical with a dip of 90°.

Only quartz grains which were indubitably detrital were used in the

preparation of diagrams (*a*) to (*d*) (Text-fig. 5), so that it is probable that they have been unaffected by the movements and the metamorphism associated with them. Owing to this restriction on the choice of grains only 100 axes are represented in (*b*). Contours have been drawn at 1 per cent intervals, the same scale of density of concentration applying to all diagrams. (*a*) to (*c*) are from sections perpendicular

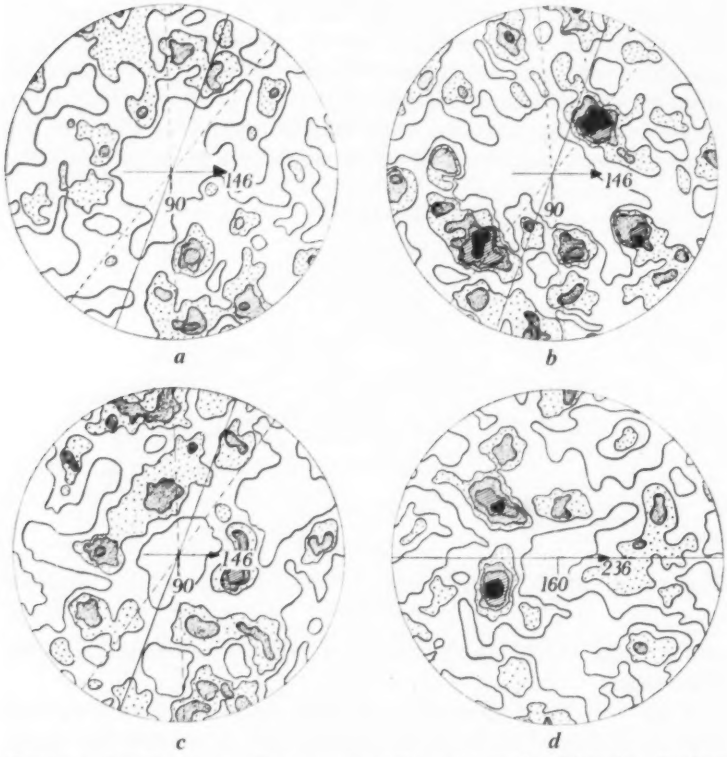


TEXT-FIG. 4.—Axes of reference for orientating the petrofabric diagrams in space.

to the strike and (*d*) is parallel to it. All are perpendicular to the schistosity.

A difficulty arises in interpreting these diagrams. Separately they show small concentrations of the axes but these are not disposed on any regular plan. Collectively, the only character they may be said to have in common is an appreciable minimum in the centre with one or two very small minimal areas irregularly distributed. It seems very doubtful indeed whether these have any genetic significance. No doubt an ingenious mind could invent a concatenation of circumstances which would bring about such a disposition of axes in quartz grains derived from crystalline rocks and ultimately deposited in a grit bed, but the more reasonable view here would be to accept the diagrams as representing a rather imperfect approximation to a chance distribution of the quartz grains. The important point is that in our interpretation of any preferred orientation in the quartz formed later during the movements we must have regard to this initial distribution of the axes in space.

Diagrams (*e*) to (*h*) (Text-fig. 6) were prepared from recrystallized quartz only, and the thin sections used were the same as those from which (*a*) to (*d*) were made. (*e*) to (*g*) are from sections perpendicular to the strike and (*h*) is parallel to it. The preparation of these diagrams was very difficult as the grains were extremely small and some are



TEXT-FIG. 5.—Continuous lines represent the megascopic schistosity. Broken lines represent the average positions of the sub-parallel sides defining the shapes of many of the grains.

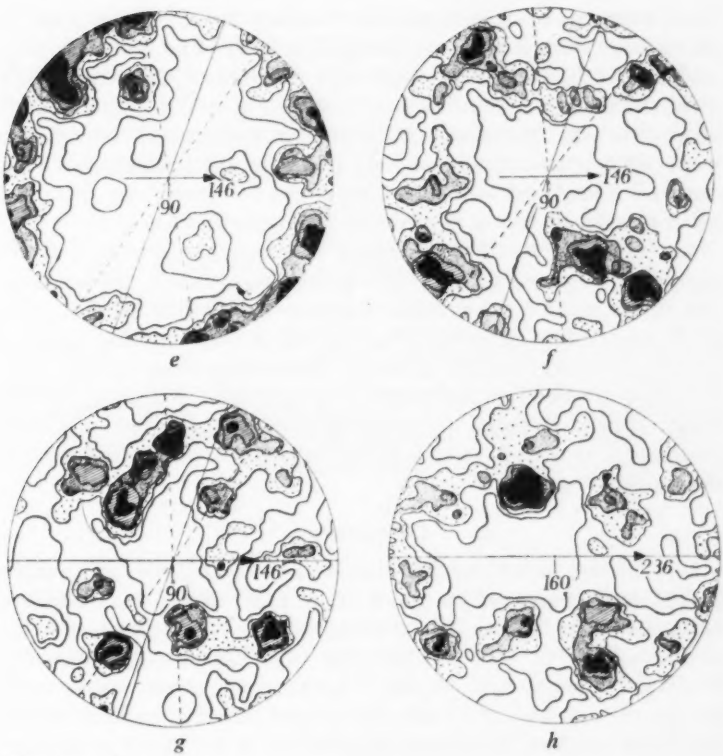
(*a*) Quartz phyllite. 200 Detrital-quartz axes. Perpendicular to strike, parallel to dip. Contours at 4, 3, 2, 1 per cent per 1 per cent area.

(*b*) Perpendicular to strike, parallel to dip. 100 detrital quartz axes. Contours at 5, 4, 3, 2, 1 per cent per 1 per cent area.

(*c*) Perpendicular to strike, parallel to dip. 200 detrital quartz axes. Contours at 4, 3, 2, 1 per cent per 1 per cent area.

(*d*) Parallel to strike, perpendicular to dip. 200 detrital quartz axes. Contours at 5, 4, 3, 2, 1 per cent per 1 per cent area.

hidden by tilts of more than 30° about the A_2 or A_4 axes of the universal stage. Some grains also had to be ruled out as one could not be quite sure that they did not belong to the original detrital quartz. These difficulties reduce the number of grains available for these determinations so that only 100 grains were measured in each case and the diagrams are not as representative as one would wish. It is difficult, however, to see how one could improve them in this respect.



TEXT-FIG. 6.—

(*e*) Perpendicular to strike, parallel to dip. 100 recrystallized quartz axes. Contours at 5, 4, 3, 2, 1 per cent per 1 per cent area.

(*f*) Perpendicular to strike, parallel to dip. 100 recrystallized quartz axes. Contours at 5, 4, 3, 2, 1 per cent per 1 per cent area.

(*g*) Perpendicular to strike, parallel to dip. 100 recrystallized quartz axes. Contours at 5, 4, 3, 2, 1 per cent per 1 per cent area.

(*h*) Parallel to strike, perpendicular to dip. 100 recrystallized quartz axes. Contours at 5, 4, 3, 2, 1 per cent per 1 per cent area.

Black, 4–5 per cent; Close stipple, 3–4 per cent; Open stipple, 2–3 per cent; Clear, 1–2 per cent; and 0–1 per cent.

All these diagrams of the reformed quartz show the same minimum concentration of the poles in the centre as do the diagrams of the detrital quartz, and it seems reasonable therefore to interpret this feature as a relic of the original structure. As this is the most striking feature of all of the diagrams it would suggest that one of the factors influencing the newly forming quartz is the lattice orientation of the quartz already there, a conclusion which certainly has nothing novel about it. Is there any sign of other influences? Diagram (*e*) certainly shows a strong tendency towards a girdle-like concentration of the axes and if the

interpretation already given of the shearing movements involved in the rock flattening is accepted, this girdle is in the plane of deformation, and thus at right-angles to what one would expect from Anderson's mechanical interpretation of the orientation of quartz grains in such an environment. Indistinct maxima can also be discerned in this girdle, some lying approximately at right-angles to the *s*-planes, but it is doubtful if any worth-while conclusion can be drawn from this since other maxima lie on one of the sets of the *s*-planes themselves.

Unfortunately the other diagrams do not lend themselves to the same simple generalization. Beyond showing a certain angular symmetry, the maxima are distributed in a quite irregular manner. (*f*) might conceivably be interpreted as a girdle either in process of evolution or of decay but this is fiction rather than fact, and certainly the other diagrams do not suggest any systematic orientation of the quartz grains. If, therefore, any of the suggested processes of purely mechanical reaction have been operative their role has in the long run been a minor one only.

Conclusions

It is difficult to see any resemblance between this relatively simple case of deformation and the purely mechanical theories that have been advanced. The model of the close-packed quartz spheres seems too naïve to help very much in picturing what has actually happened. It certainly cannot hold for the original quartz grains which show no sign of rotation, and in the very fine-grained recrystallized quartz the radial width of the surface irregularities of the grains is so great that there is nothing corresponding to the core which Anderson considers is the element that rotates. There is some definite evidence that in the recrystallization the original orientation of the quartz crystals is of importance but, as the study can only be a statistical one, we do not know just how this control operates. It may mean nothing more than that a fair percentage of the fine-grained quartz represents minute relics of the original grains. There is some evidence also that a tendency exists in the new crystallization of the quartz for the grains to grow with their optic axes lying roughly in a girdle which falls in the plane of deformation. But this tendency is readily obliterated by other factors, at present obscure but the effect of which is to distribute the axes irregularly in space.

In these rocks one of the most noticeable features both in the field and under the microscope is the ease with which quartz recrystallizes, and this recrystallization in many places can be seen to have taken place quite apart from the movements which the rocks have undergone. Whatever the details of its physical chemistry the process falls into the general category of solution and reprecipitation and there

seems therefore no reason for considering that these processes cease to be dominant when movement takes place. Undoubtedly the thermodynamics of the reactions must be much more complicated when the strain energy must also enter into the equilibrium, but it seems certain that no purely mechanical theory can be adequate to explain the texture of these schists.

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Mugearites and Oligoclase-basalts

By A. Kingsley Wells

Abstract

A plea is made for the wider use of concise descriptive phrases instead of rock-names of the conventional type, which are usually uninformative. The writer's case is discussed in relation to the so-called " mugearites ".

In the *Geological Magazine* for last year Professor F. Walker discussed the synonymy of " mugearite " and " oligoclase-basalt ". Later his conclusions were briefly discussed by Dr. A. G. MacGregor.

Summarily Walker shows that rocks to which these two terms have been applied agree closely in chemical composition, but differ appreciably in their " fabric and mineralogy ". By plotting chemical composition on triangular diagrams, Walker has no difficulty in establishing the truth of his first point: the two types are indistinguishable chemically. Because both are basic and in the " fine-grain " category both, in my opinion, should be covered by the same " generic " term, and this is where I join issue with both Walker and MacGregor. I feel that the relative status of these two terms is either not appreciated, or if appreciated, is certainly not clearly stated in either communication. It seems to me that the relationship between " oligoclase-basalt " and " mugearite " is precisely that of a *genus* to a *species* in biological science. All these rocks, from fundamental considerations of composition and texture, belong to the " genus " oligoclase-basalt. The " specific " characters which give individuality to mugearites among the oligoclase-basalts involve features seen in the field, in hand specimens, and in thin sections, as detailed by Walker and MacGregor. It may well be that among the oligoclase-basalts there is scope for establishing a number of " species " sufficiently distinctive in the details of mineral composition and textural quality to justify using a number of specific type-names; but at the moment only mugearite seems to have received this recognition.

Like Walker, I firmly believe that it would be a serious mistake to attempt to substitute the specific term " mugearite " for the generic term " oligoclase-basalt ". All mugearites are oligoclase-basalts; but only some oligoclase-basalts are mugearites. I believe that nothing would be lost and much gained in clarity if for " mugearite " we substituted " oligoclase-basalt of Mugeary type ".

The significance of speaking of a particular oligoclase-basalt as being " of Mugeary type " is precisely the same as in the case of normal basalts, said to be, for example, of Dunsapie, Markle, or Jedburgh type, defined on textural criteria. All petrologists agree, thank goodness,

that these rocks are first and foremost *basalts*; and nobody has been foolhardy enough to propose disguising this fundamental fact by referring to them as dunsapieites, markleites, or jedburghites. Then logically why should a different principle be applied to the rocks in question? The facts concerning the essential chemical composition, the mineral content and the textural quality should be considered in that order in all problems of petrographic nomenclature. If this procedure is followed in the case under discussion the conclusion seems inevitable that petrologists could with advantage dispense with the term mugearite, and use in its place the phrase " oligoclase-basalt of Mugeary type (Harker, 1904) ".

It seems to be generally agreed that on the mineralogical side the distinctive feature of the Mugeary type of oligoclase-basalt is the occurrence of microphenocrystic olivine and of small quantities of hornblende and biotite. On the textural side emphasis is laid on the occurrence of a well-developed fluxional structure which, in turn, imparts a distinctive platy fracture and silky lustre to the rocks. The question arises whether, in the absence of this fluxion structure, one must employ another type-name. In the abstract I think it probable that rocks exist which are identical in mineral and chemical composition with the type rocks from Mugeary, Skye; but which differ texturally from them. In such a case—hypothetical admittedly—is the failure to come up to specification in this one detail justification for putting the rock into a different pigeonhole? If this is considered to be so, then the use of the term " of Mugeary type " turns solely on the presence of well-developed fluxion structure. It appears to me that such a usage is too exclusive; that any rock-name should carry the implication of a specified composition, both chemical and mineral; and that, within the appropriate grain-size group, variation in texture should be covered by the use of appropriate textural qualifiers. In other words, while I would permit no departure from the specification as regards mineral composition of the rock, it seems to me to be reasonable to allow some latitude as regards texture. When all said and done, fluxional parallelism of microlites is of no genetic significance: and all degrees of parallelism may be seen even in specimens of trachytes. This expresses my view; but Walker (and doubtless many others) think otherwise, for in his final definition of " mugearites " he includes the phrase " with well-marked trachytic feldspar laths in thin section ". On a point of detail surely these words are liable to misinterpretation, and are therefore out of place in a scientific definition. " Trachytic feldspar laths " is, to me, synonymous with " sanidine microlites ", for the latter are the feldspar laths of typical trachytes. Walker evidently means " oligoclase microlites with well-developed fluxion structure ".

In his contribution to this discussion MacGregor refers to certain rocks which are transitional between mugearites and " fine-grained basalts with fluxional parallelism of feldspars ". It is not made clear whether they are transitional in regard to composition or to texture; but in either case in my opinion the term to which he gives his blessing —" basaltic mugearites " is very inadequate. " Basaltic," used as a textural qualifier, is meaningless when one remembers the varying role of phenocrysts (both mega- and micro-) and of glass and mesostasis in different basalts, to say nothing of special textures including the ophitic and intergranular, and the varying degrees of perfection of flow phenomena. There is no single word which will convey the right impression of the textural quality of the rock that MacGregor has in mind, though a carefully worded *phrase* would do so. In problems of rock-nomenclature it is all too easy to be concise to the point of becoming meaningless. This is a case in point. " Fine-grained microphyric fluxional basalt " conveys a reasonably comprehensive picture of a rock possessing those features that MacGregor has observed. To saddle it with a name of the conventional type-locality variety would be the reverse of helpful: it would tell us precisely nothing.

After writing the above, I have re-read a paper I contributed to the *Geological Magazine* nearly thirty years ago, and which deals with the nomenclature of " mugearites ". It is satisfying to find that in that period of time nothing has occurred to cause me to change my views concerning the principles then stated.

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The Clinopyroxenes of the Garbh Eilean Sill, Shiant Isles

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Abstract

Ten clinopyroxenes have been investigated chemically and optically. Eight of these were separated from the rocks of the Garbh Eilean sill and two from other rocks relevant to this inquiry into the trend during crystallization of pyroxenes in minor basic intrusions of mildly alkaline and undersaturated type.

Introduction

A SYSTEMATIC reinvestigation of the geology of the Shiant Isles was initiated by Dr. H. I. Drever in 1949. A detailed optical study of the olivines has been published (Johnston, 1953) and the present study of the clinopyroxenes is a further part of the general plan of research.

The compositions of the pyroxene phases crystallizing from saturated basaltic magmas of tholeiitic type have been studied in great detail during the last twenty years and Poldervaart and Hess (1951) have recently reviewed the present position. It was because of the comparative lack of data on pyroxenes crystallizing from basaltic magma of the undersaturated and more alkali-rich type (crinanitic and teschenitic) that the writer undertook this investigation.

Ten pyroxenes have been separated and analysed from the rocks of the Shiant Isles. Six were separated from picrite, picrodolerite, and crinanite specimens selected at intervals from the serial collection through the Garbh Eilean sill (Drever, 1953). One was separated from a pegmatite patch in the picrite, another from a vein cutting the picrodolerite, and another from a pyroxene-rich laminated layer in the Eilean Mhuire sill (Walker, 1930).

In addition to pyroxenes from the Shiant Isles, a green pyroxene from an orthophyre vein in the Portrush olivine-dolerite sill (Harris, 1937), was also analysed. The mineral paragenesis of this vein, and the fact of its occurrence in an undersaturated basic sill of Tertiary age, suggested that an analysis of this green pyroxene would be relevant to the present investigation. The somewhat similar green pyroxene, developed in association with crinanite-pegmatite and argillaceous hornfels on Eilean an Tighe, has yet to be found in an amount adequate for separation and chemical analysis.

The green pyroxenes, developed in the analcite-syenite (and its segregation patches) of the Eilean Mhuire sill are, according to Walker (1930), aegirine-augite and aegirine. Until a more detailed re-investigation of these rocks has been made it is considered inadvisable to separate a pyroxene from the rock specimens so far collected which might prove later to be only localized in occurrence and unrepresentative.

Seven of the rocks from which the pyroxenes were extracted and two associated olivines have also been chemically analysed by the writer. Some data from these analyses have been used in the discussion of the crystallization trend of the pyroxenes. The full analyses will be published in later papers dealing with the detailed petrology of the sill.

Methods

All refractive indices were determined by immersion methods, usually on crushed grains; the refractive indices of the oils were measured on a Leitz-Jelley refractometer in sodium light. The probable error is $\pm$ 0·003.

The optic axial angles of the pyroxenes were measured on a 4-axis Universal stage in sodium light. Wherever possible, direct measurement of 2H was made by the conoscopic method of Hallimond (1950) and the error is $\pm \frac{1}{2}°$. Since the pyroxene crystals increase in size in the higher rocks the number of individual crystals in a thin section decreases and, as they are frequently not suitably orientated for a direct measurement of 2H, an indirect method had to be used. The error of these estimations is $\pm$ 2°. As none of the pyroxenes is twinned it was not possible to measure the extinction angle ($\gamma \wedge c$) by the accurate methods of Nemoto (1938) and Turner (1942). Extinction angles were determined by plotting the cleavages and locating the pole of the *c*-axis.

The compositions of the feldspars were determined by Universal stage methods and checked by refractive index measurements.

The Chayes point-counter method (Chayes, 1949) was used to determine the percentage by volume of the minerals in the rocks. Owing to the large size of the ophitic pyroxene and ophitic olivine crystals in the upper crinanite it was found necessary to use sections up to 30 sq. cm. in area before the approximate modal composition of the rocks could be determined. The total traverse was 80–100 times the grain size and the error is estimated to be about 5 per cent.

Separation of the minerals was effected by removal of the magnetic iron ore by a powerful magnet, followed by flotation in bromoform and methylene iodide and repeated centrifuging in Clerici solution. The samples obtained by these methods were finally purified by handpicking.

Petrological Relations and Mineral Parageneses

Modal Variation of Minerals throughout the Sill.

The amount of olivine falls sharply as the picrite-picrodolerite junction is crossed and continues to decrease until, in the upper crinanite, it is reduced to 14 per cent. The amount of pyroxene increases abruptly over the junction from 8 per cent in the picrite to 20 per cent

in the picrodolerite, reaches a maximum of 23 per cent in the lower crinanite, and then begins to decrease. Feldspar increases abruptly over the junction from 19 per cent in the picrite to 28 per cent in the picrodolerite in which there is a rapid upward increase to 51 per cent. The amount of plagioclase does not vary significantly from this figure throughout the upper part of the picrodolerite and all of the crinanite. Iron ore increases to 6 per cent in the picrodolerite and gradually rises to 8 per cent in the crinanite.

Picrite.

In thin section the picrite shows large irregular crystals of pyroxene (1) ($Ca_{47}Mg_{42}Fe_{11}$), up to 1 cm. long, enclosing small rounded grains of fresh magnesian olivine. The pyroxene is pale purplish-brown in colour, slightly pleochroic, and has well-developed {110} cleavages. The feldspar (An_{80}) occurs as large crystals in poikilitic relation to olivine and iron ore. No zoning has been detected in the feldspar or in the pyroxene. The approximate relative amounts in weight-per cent are 69 olivine, 19 feldspar, 8 pyroxene, and 4 iron ore.

Picrodolerite.

Above the picrite-picrodolerite junction large crystals of pale purplish-brown pyroxene (17) ($Ca_{44\cdot5}Mg_{43\cdot5}Fe_{12}$), with well-developed cleavages, are in ophitic relation to small laths of feldspar zoned from An_{80} to An_{55}. The pyroxene still encloses rounded grains of olivine. There are small inclusions of iron ore in the olivine and less frequently in the pyroxene and feldspar. The approximate relative amounts in weight- per cent are 47 olivine, 20 pyroxene, 28 feldspar, and 8 iron ore.

Pyroxene increases in amount through the picrodolerite and the ophitic relation to plagioclase becomes, if anything, more pronounced. No zoning has been detected in the clinopyroxenes crystallizing at a height of 75 feet above sea-level although, in plane-polarized light, adjacent sectors of the pyroxene crystals show a slight change in colour. Both portions have the same optic axial angle but it is found that there is a slight deorientation of adjacent parts of the crystal when the optic elements are plotted on stereographic projection. The olivine decreases in amount and is zoned from a magnesian core to a more iron-rich margin. Crystals of iron ore increase in size and become more skeletal.

The picrodolerite located at a height of 135 feet above sea-level contains large crystals of ophitic clinopyroxene the cores of which have an optic axial angle ($2V\gamma$) of $48\frac{1}{2}°$ and the margins an angle of 51°. These measurements were made by rotation from one optic axis to the other and they indicate the beginning of a core and margin type of zoning. The olivine is zoned from Fa_{23} at the core to Fa_{47}

(Johnston, 1953) at the margin and the feldspar is zoned from An_{60} to An_{30}.

Crinanite.

The picrodolerite passes into crinanite by a gradual decrease in the modal amount of olivine and the pyroxene is enclosing so much feldspar that the texture might be more precisely termed poikilophitic. As described by Johnston (1953) a similar relation develops between the olivine and feldspar. In the lower crinanite the pyroxene (25) ($Ca_{44}Mg_{36\cdot5}Fe_{19\cdot5}$) is brownish in colour and slightly pleochroic. At the margins of the crystals the colour changes to pale green. Progressively higher in the crinanite the extent of the green zone increases, the colour deepens, and pleochroism is more pronounced (X = pale green, Y = green, Z = green). The clinopyroxene in a specimen (31), 325 feet above sea-level, is zoned with $2V\gamma = 52°$ in the core and $2V\gamma = 56°$ in the outer zone. It proved possible to separate this clinopyroxene into a light fraction (31L) ($Ca_{45}Mg_{41}Fe_{14}$) and a heavy fraction (31H) ($Ca_{44}Mg_{30\cdot5}Fe_{25\cdot5}$). Although the heavy fraction is the most iron-rich of the analysed pyroxenes from the Garbh Eilean sill it is an average composition of the outer zones and probably represents less than the maximum degree of iron-enrichment. The associated olivine is zoned from Fa_{37} to Fa_{96} (Johnston, 1953), and the feldspar from An_{80}–An_{30}. The approximate relative amounts in weight-per cent are 14 olivine, 18 pyroxene, 55 feldspar, 10 iron ore, and 2 analcite.

Pegmatite Patch in the Picrite.

The pyroxene (P_1) in this very coarse-grained rock, although it may develop between large plagioclase crystals, is not in ophitic relation to them. It is more pleochroic (X = purple, Y = brown, Z = brown-purple) than any other pyroxene crystallizing in the sill and frequently builds long prisms occasionally rimmed by a very thin greenish margin. The olivine has crystallized as relatively large grains which are not enclosed by the pyroxene or the anorthitic feldspar (An_{95}—determined by refractive index $\gamma = 1{\cdot}585$). According to Johnston (1953) the composition was Fa_{12}. As his optical determinations were all made on γ sections, Mr. Johnston carefully redetermined the optic axial angle on a number of new thin sections in which α sections of olivine were present. The average, and now corrected, values of the optic axial angle indicate a composition Fa_{16}. There is thus no appreciable difference in composition between this olivine and the olivine of the surrounding picrite.

Vein in the Picrodolerite.

This specimen was collected in 1952 from a somewhat irregular

vertical vein in the picrodolerite about 10–15 feet above the picrite-picrodolerite junction. It lies immediately above, and appears to be a continuation of a vertical vein cutting the picrite.

The pyroxene (P_2) crystallizes as large, pale purplish-brown, slightly pleochroic crystals. They are slightly zoned from a darker core through a pale brown intermediate zone which gradually becomes pale greenish. There are some tiny grains of olivine (too small for optical determinations) embedded in an orange-yellow serpentine. Large crystals of much analcitized feldspar, containing small needles of apatite, surround the pyroxene. There is abundant skeletal and acicular iron-ore which transects the pyroxene and feldspar.

Layered and Laminated Zone in the Lower Sill, Eilean Mhuire.

The most abundant mineral in mafic layers of this coarse-grained rock is clinopyroxene which occurs as columnar crystals with their *c*-axes approximately coplanar. The pyroxene prisms are 1–1½ cm. long, pale greenish-purple in colour, feebly pleochroic, and very slightly zoned. They enclose small crystals of iron ore. The pyroxene is surrounded by large crystals of iron ore, and feldspar which is almost wholly converted to zeolites. Small needles of apatite and a minor amount of yellow-orange serpentine occur in the altered feldspar.

Orthophyric Vein, Portrush Sill, Co. Antrim.

The writer collected a specimen of the most persistent of the orthophyre veins, the " Great Vein ", near the Peak Pool. In hand specimen the rock when fresh is dark green in colour and fine-grained. Microscopically it shows small crystals of green clinopyroxene (P_3), zoned from a very pale green core to a light green margin, set in a matrix of stumpy prisms of albitic plagioclase. The pyroxene contains tiny inclusions of iron ore. There is abundant orange-yellow serpentine in which small rounded grains of ferrohortonolite (Fa_{75}) can be identified. There is a little interstitial quartz between the feldspar prisms.

The Clinopyroxenes

Discussion of Analyses.

Warren and Briscoe (1931) showed that acmite, jadeite, spodumene, augite, diopside, hedenbergite, and clinoenstatite had similar structures typified by diopside. They suggested as a general formula for the monoclinic pyroxenes:—

X_mY_{2-m} (Si, Al)$_2$(O, OH, F)$_6$ where $m = 1$ or $0{\cdot}0$ and X = Na, Ca, (K), (Mn), and Y = Mg, Fe^{2+}, Fe^{3+}, Al, Ti, Mn.

It has been shown by Dixon and Kennedy (1931), Barth (1931), Deer and Wager (1938), and Muir (1951), that in some cases it is necessary to assume a replacement of Si by Ti in order to adjust the analysis to the formula.

Chemical analyses and optical properties of the clinopyroxenes are tabulated in Table 1. The analyses reveal that SiO_2, Al_2O_3, and TiO_2 are very nearly constant in amount in the pyroxenes crystallizing throughout the sill. In some of the pyroxenes Ti apparently replaces Si in tetrahedral co-ordination (Table 2). The amount of TiO_2 in the

TABLE 1.—ANALYSES AND OPTICAL PROPERTIES OF CLINOPYROXENES

	1	17	20	25	29	31L
SiO_2	49·20	49·26	49·85	50·29	49·24	49·50
Al_2O_3	3·33	3·01	3·75	2·82	3·32	3·92
TiO_2	1·83	1·45	1·37	1·33	1·36	1·24
Fe_2O_3	1·85	2·68	2·55	1·76	2·31	2·27
FeO	5·30	5·35	6·09	9·75	10·98	6·60
MnO	0·18	0·14	0·19	0·26	0·20	0·30
MgO	15·03	15·62	14·38	12·49	12·69	13·79
CaO	23·33	22·29	21·76	21·14	19·82	21·54
Na_2O	0·40	0·45	0·42	0·44	0·12	0·31
K_2O	tr	tr	tr	tr	0·06	tr
H_2O-	0·03	0·05	0·01	nil	0·10	0·04
H_2O+	—	—	—	—	—	—
	100·48	100·30	100·37	100·28	100·20	99·51
α	1·697	1·698	1·698	1·700	*1·698	1·700
β	1·707	1·709	1·706	1·707	—	1·710
γ	1·722	1·723	1·720	1·724	†1·730	1·725
$\gamma - \alpha$	0·025	0·025	0·022	0·024	—	0·025
$2V\gamma$	48	53	50	50–53	50	52
$\gamma \wedge c$	41	42	44	44	40	44
Atomic %						
Ca	47	44·5	45	44	42	45
Mg	42	43·5	41·5	36·5	37	41
Fe	11	12	13·5	19·5	21	14
$\frac{(FeO + Fe_2O_3) \times 100}{FeO + Fe_2O_3 + MgO}$						
Pyroxene	32	34	37·5	48	51	39
Rock	34	36	52	67	68	73
Olivine	32·5	35	43	74	78	78

* Minimum
† Maximum

	31H	P_1	P_2	Mh	P_3
SiO_2	49·31	49·40	49·52	50·29	48·13
Al_2O_3	2·62	3·92	3·81	1·47	1·51
TiO_2	1·37	2·25	2·18	1·23	0·46
Fe_2O_3	1·50	1·18	2·31	1·03	2·48
FeO	13·97	7·18	6·57	11·75	23·27
MnO	0·25	0·13	0·09	0·25	0·66
MgO	10·26	13·90	13·35	12·47	4·56
CaO	20·47	21·47	21·73	21·07	18·46
Na_2O	0·31	0·70	0·75	0·49	0·83
K_2O	tr	tr	tr	tr	0·30
H_2O-	0·05	nil	nil	0·05	0·10
H_2O+	—	—	—	0·27	—
	100·11	100·13	100·31	100·37	100·76*

* Another analysis of this pyroxene will be made and published in a paper dealing with the petrology of the Garbh Eilean sill.

α	1·705	1·698	1·695	1·702	1·718
β	1·711	1·705	1·706	1·708	1·728
γ	1·732	1·721	1·720	1·725	1·748
$\gamma - \alpha$	0·027	0·023	0·025	0·023	0·030
$2V\gamma$	56	50	49–57	51–55	49–59
$\gamma \wedge c$	45	44	43–53	44–45	44–46
Atomic %					
Ca	44	45	46	43	41
Mg	30·5	40·5	40	36·5	14
Fe	25·5	14·5	14	20·5	45
$\frac{(FeO + Fe_2O_3) \times 100}{FeO + Fe_2O_3 + MgO}$					
Pyroxene	60	37·5	40	50·5	85
Rock	73	—	—	—	97
Olivine	78	25	—	—	84·5

pyroxenes crystallizing in the pegmatite patches in the picrite is relatively high compared with the amount in the other pyroxenes of the sill. The proportion of Al replacing Si in the *z* group is of the order of 7 per cent. The major variations are in the amounts of Ca^{2+}, Mg^{2+}, Fe^{2+}.

In the pyroxenes from the picrite and picrodolerite the *X* group decreases only slightly from 0·95 to 0·91 and replacement occurring at this stage must be mainly the substitution of Fe^{2+} for Mg. Progressively upward in the crinanite, the *X* group decreases to 0·81 and here the iron is introduced at the expense of calcium. Analysis of the outer zones of the pyroxene in the upper part of the crinanite (31H), however, shows that the *X* group increases once more while Mg decreases, its place being taken by Fe. The core of this pyroxene

TABLE 2.—FORMULAE OF CLINOPYROXENES ON BASIS OF SIX OXYGEN ATOMS

		I	17	20	25	29	31L	31H	P_1	P_2	Mh	P_3
z	Si	1·829	1·830	1·849	1·900	1·865	1·857	1·900	1·840	1·843	1·912	1·927
	Al	0·143	0·129	0·151	0·100	0·135	0·143	0·092	0·160	0·157	0·068	0·073
	Ti	0·028	0·041	—	—	—	—	0·008	—	—	0·020	—
Y	Al	—	—	0·014	0·023	0·010	0·028	—	0·010	0·008	—	—
	Ti	0·022	0·002	0·038	0·036	0·039	0·034	0·034	0·063	0·063	0·014	0·013
	Fe^{2+}	0·049	0·076	0·071	0·050	0·064	0·063	0·042	0·035	0·063	0·027	0·077
	Fe^{3+}	0·165	0·167	0·189	0·306	0·348	0·207	0·451	0·224	0·206	0·373	0·778
	Mn	0·006	0·005	0·007	0·007	0·005	0·009	0·007	0·004	0·002	0·007	0·022
	Mg	0·838	0·872	0·799	0·707	0·716	0·776	0·593	0·778	0·750	0·712	0·274
X	Ca	0·930	0·887	0·863	0·855	0·804	0·866	0·850	0·856	0·864	0·858	0·793
	Na	0·027	0·031	0·027	0·031	0·010	0·023	0·023	0·049	0·054	0·027	0·062
	K	—	—	—	—	—	—	—	—	—	—	0·014
	z	2·00	2·00	2·00	2·00	2·00	2·00	2·00	2·02	2·00	2·00	2·00
	XY	2·04	2·04	2·01	2·02	2·00	2·01	2·00	2·01	2·01	2·02	2·03

I Pyroxene from picrite 0 feet above sea-level, Garbh Eilean.
17 ,, ,, picrodolerite 38 feet above sea-level, Garbh Eilean.
20 ,, ,, ,, 75 feet above sea-level, Garbh Eilean.
25 ,, ,, crinanite 190 feet above sea-level, Garbh Eilean.
29 ,, ,, ,, 270 feet above sea-level, Garbh Eilean.
31L, 31H ,, ,, ,, 325 feet above sea-level, Garbh Eilean.
P_1 ,, ,, pegmatite patch in picrite, 2 feet above shingle beach, S. end of Garbh Eilean.
P_2 ,, ,, vein cutting picrodolerite, SE side of Garbh Eilean.
Mh ,, ,, the layered and laminated zone in the lower sill, Eilean Mhuire
P_3 ,, ,, a ferroaugite-ferrohortonolite-orthophyre vein, Portrush sill.

(31L) is very similar in composition to the pyroxene in the picrodolerite. The analysis of the green pyroxene from the Portrush orthophyre vein reveals that Mg is largely replaced by Fe^{2+} with the *X* group decreasing and greater substitution of $Na^{+} + K^{+}$ for Ca^{2+}.

According to Edwards (1942) Fe^{2+} would replace both Mg and Ca in the early stages. Replacement of Ca by the smaller Fe ion could continue with increasing distortion of the structure until a limiting value is reached beyond which further introduction of Fe^{2+} in place of Ca would render the structure unstable. This stage is probably reached in the pyroxene from rock 29. Further enrichment in Fe^{2+} can only take place at the expense of the Mg^{2+} ion. Since the Fe^{2+} ion is slightly larger than the Mg^{2+} ion the interionic distances between the chains would be increased and an increasing proportion of Ca would enter the structure as in pyroxene 31H.

The refractive indices are notably higher than those of clinopyroxenes, with a similar degree of iron enrichment, in tholeiitic rocks. This increase in the values of the refractive indices has been observed, according to a number of earlier investigations, in other analysed pyroxenes and in each case there is a relatively greater amount of TiO_2.

Increasing enrichment in iron enlarges the optic axial angle ($2V\gamma$) but the range of values from diopside to hedenbergite is small and so this property is of little help in determining the composition of the pyroxene.

The relatively high refractive indices of the clinopyroxenes which are enriched in TiO_2 re-emphasize that diagrams which correlate refractive indices and optic axial angles with chemical composition (Muir, 1951) cannot be used to determine the composition of titanaugite from its optical properties.

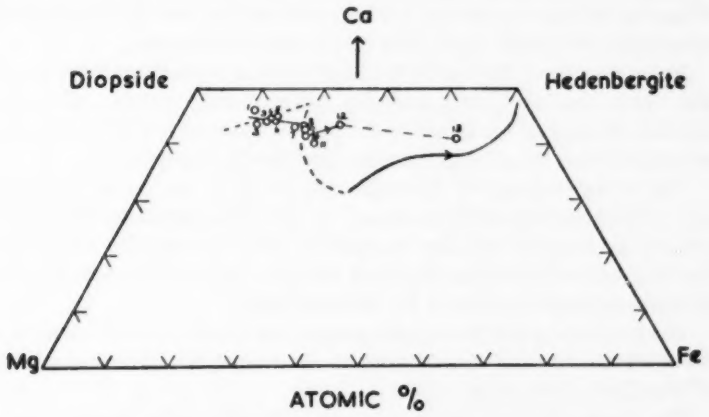
Trend of Crystallization.

The compositions of the pyroxenes have been calculated on a basis of Ca + Mg + Fe = 100, where Fe includes $Fe^{2+} + Fe^{3+}$ + Mn (Hess, 1949), and plotted with these elements as co-ordinates in Text-fig. 1.

The trend of the pyroxenes is compared with that in the Skaergaard intrusion (Muir, 1951). A pyroxene from the Tertiary olivine-gabbro dyke of Camas Mòr, Muck (Tilley, 1952) is also included.

In the Garbh Eilean sill it seems probable that olivine crystallized for a considerable period before the appearance of clinopyroxene and there is no evidence of a reaction relationship between them. Early crystallization of the Ca-free olivine would reduce the Mg-content and increase the molecular proportion of lime in the magma. When the pyroxene began to appear it was thus a Ca-rich member of the

diopside-hedenbergite series which crystallized in cotectic relationship with a calcic feldspar (An_{80}). In the lowest part of the picrodolerite the clinopyroxene crystallized with a decreased Ca-content and thenceforth there was a progressive replacement of Mg by Fe while the Ca content remained almost constant and the trend of the



TEXT-FIG. 1.—Trend of the clinopyroxenes in the Garbh Eilean sill compared with the clinoproxene trend in the Skaergaard intrusion, east Greenland.

1, pyroxene (1) ; 2, pyroxene (17) ; 3, pyroxene (20) ; 4, pyroxene (31L) ; 5, pyroxene (P_2) ; 6, pyroxene (P_1) ; 7, pyroxene of 31 analysed by I. D. Muir ; 8, pyroxene (25) ; 9, pyroxene (Mh) ; 10, pyroxene (29) ; 11, pyroxene of olivine-gabbro Camas Mòr ; 12, pyroxene (31H) ; 13, pyroxene (P_3).

crystallization became almost parallel to the diopside-hedenbergite join. The feldspar laths, in ophitic relation to the pyroxenes, are zoned from An_{80} to An_{55}. The amounts of feldspar and pyroxene increased while olivine decreased.

In the crinanite the pyroxene became still poorer in lime and the zoning in the feldspar increased to An_{80-30}. At a height of 325 feet above sea-level the core of the pyroxene is similar in composition to the pyroxene which crystallized in the picrodolerite while the outer zones are enriched in Fe at the expense of Mg, thus bringing the trend nearer to hedenbergite. The optic axial angle ($2V\gamma$) and the extinction angle ($\gamma \wedge c$) are only slightly greater for the margin than for the core and, since the chemical analysis (31H) does not show an increase in Na_2O or in Fe_2O_3 it would appear that there is, if any, a very limited introduction of the aegerine molecule. It seems definitely to be established that the zoning, and therefore the trend, is toward ferroaugite.

The Skaergaard intrusion is of tholeiitic type (Tilley, 1950) and relatively highly fractionated, but some comparison with the Garbh Eilean sill is valid. Muir (1951) concludes that during the crystallization of the Middle Gabbros, the liquid moves into the field where clinopyroxene alone can crystallize. This leads to an increase in the amount of pyroxene crystallizing with a concomitant fall in its Ca content. When the olivine reappears in the ferrogabbros, the amount of pyroxene diminishes but at the same time its Ca content increases.

In the magma of the Garbh Eilean sill olivine crystallizes throughout the whole cooling history and the clinopyroxene remains relatively Ca-rich, though in the crinanite there is evidence of a similar but less emphatic trend to a clinopyroxene with a lower content of Ca.

The clinopyroxenes of the pegmatite patch in the picrite and the vein cutting the picrodolerite are very similar in composition. The slight zoning to greenish margins suggests a late iron-enrichment which has not, according to the chemical analyses, significantly affected the position of these pyroxenes on the trend line.

The pyroxene from the layered zone in the Eilean Mhuire sill shows no marked chemical dissimilarity to those in the uniform crinanite of the Garbh Eilean sill.

The green pyroxene in the Portrush orthophyre vein shows a high degree of replacement of Mg by Fe together with a relatively lower Ca content, and its composition is such that it lies near the trend of the pyroxenes crystallizing in the ferrogabbros of the Skaergaard intrusion.

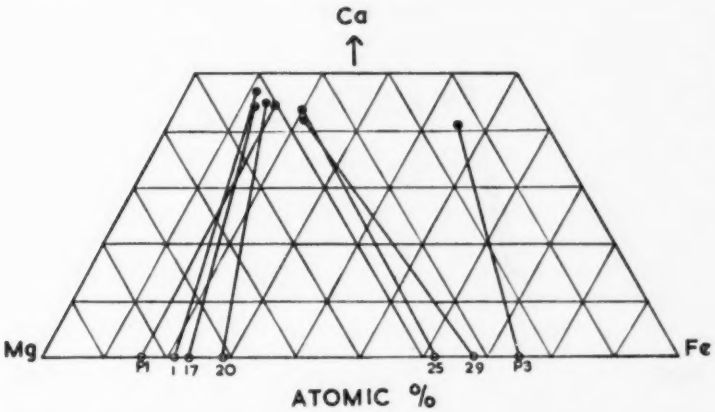
Paragenesis with Olivine.

The olivines in the picrite and the lower picrodolerite were separated and analysed. The composition of the latter is in close agreement with the composition inferred by Johnston (1953) from a study of the optical properties. Chemical analysis of the olivine in the picrite (1) shows it to be more iron-rich (Fa_{21}) than is apparent from the optical properties alone (Fa_{17}). Separation in heavy liquids may have resulted in a concentration of the grains which Johnston determined as Fa_{21}.

In the upper part of the picrodolerite and in the crinanite the range of the zoning is such that it is unlikely that separation and chemical analyses would result in an accurate determination of the composition of the olivines. The chemical compositions of the pyroxenes and the parent rocks and the proportions by weight of the minerals (calculated from the mode) have been determined.

From these data the MgO content of the olivines can be calculated, and hence, from the curves of Poldervaart (1950), the corresponding molecular percentage of Fa. The validity of the method depends to a large extent on the accuracy of the mode which, owing to the very large size of the olivines and pyroxenes in the higher rocks, has an error

estimated to be about 5 per cent. The error in the method is likely to increase as the proportion of olivine in the rock increases. When the composition of the olivine in specimen 17 is calculated by this method, it is found to have a composition of Fa_{22} compared with $Fa_{21\cdot4}$ from chemical analysis of the separated mineral. When modal analyses of the crinanite were made it was found that repeated determinations



TEXT-FIG. 2.—Relationship between clinopyroxenes and their associated olivines.

of any one rock gave an almost constant olivine plus pyroxene value. Even assuming an error of 30 per cent in the modal estimation of olivine then, in specimen 29 for example, the limits of the content of Fa would be Fa_{67}–Fa_{70}, while the value recorded as the true value is Fa_{68}. Hence it is considered that the method gives a fair approximation to the average composition of the olivines crystallizing in any given rock. The relationship between the clinopyroxene and the associated olivine is set out diagrammatically in Text-fig. 2.

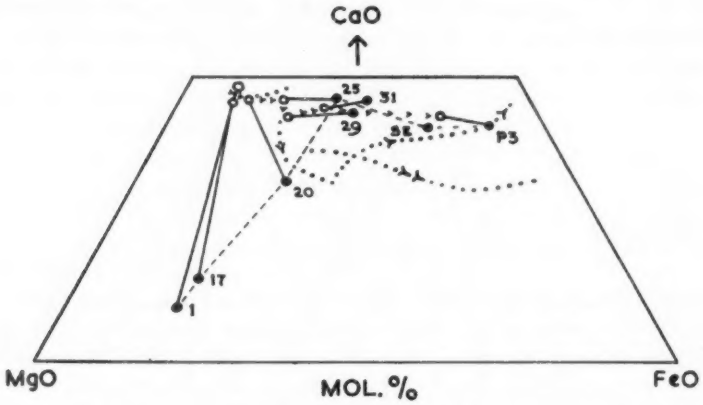
As in rocks of tholeiitic parentage the olivines with the exception of that from the pegmatite patch in the picrite, are richer than the associated clinopyroxenes in iron relatively to magnesium.

Relationship to the Parent Rocks.

In Text-fig. 3 the trend of the pyroxenes and the corresponding compositional variation of the parent rocks are plotted on the basis of molecular percentages of CaO, MgO, FeO. Relevant trends from the saturated Skaergaard magma are added for comparison.

The trend of the pyroxene crystallization is much more uniform in direction than the curve showing the progressive change in the

composition of the parent rocks. Simultaneously with the rapid decrease in MgO and increase in CaO, indicated by the curve for the parent picrite and picrodolerite, the clinopyroxenes show a slight fall in the wollastonite, and a small increase in the ferrosilite, molecules. The rapid increase in CaO continues with a correspondingly large decrease in MgO and a slight increase in FeO through the formation of the



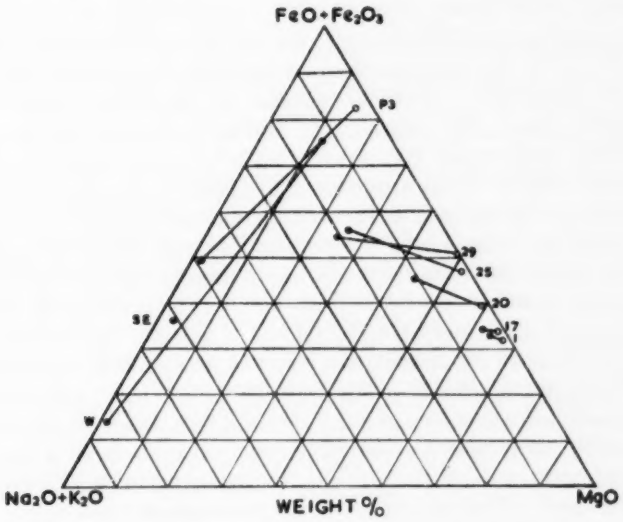
TEXT-FIG. 3.—Relationship between the trend of pyroxene crystallization and the compositional variation of the parent rocks.

» o » clinopyroxene trend.
- - ● - - parent rock variation.
• • › • • Skaergaard clinopyroxene trend.
• • » • • Skaergaard residual liquids trend.
——— tie line.
SE Segregation in analcite-syenite of Eilean Mhuire sill: analyst, E. G. Radley (Walker, 1930).

picrodolerite and lower crinanite. During the development of the upper crinanite the percentage of CaO remains almost constant and FeO increases slightly at the expense of MgO. The differences in the amounts of lime in the pyroxenes and the parent rock show a progressive change. The difference is greatest in the pyroxene crystallizing in the picrite and decreases rapidly upward through the picrodolerite until, in the crinanite, the amounts in the pyroxene and parent rock are almost equal. In the case of the Portrush orthophyre the percentage of lime is slightly greater in the pyroxene than in the parent rock. The amount of ferrous iron in the clinopyroxenes is less than the amount in the parent rock. In the picrite the difference is small but it increases to a maximum in the picrodolerite, and then decreases in the crinanite. The diagram emphasizes in a spectacular and petrogenetically significant manner how very much more magnesia there is in the

picrite compared with its pyroxene. Magnesia decreases rapidly in the picrodolerite and the amounts in the pyroxene and parent rocks, crystallizing at 75 feet above sea-level, are almost equal. Thenceforth the ratio is greater in the clinopyroxene than in the parent rock.

The ratio $(FeO + Fe_2O_3)100/FeO + Fe_2O_3 + MgO$ determines the progressive enrichment of total iron oxides with respect to magnesia.



TEXT-FIG. 4.—Relationship between the trend of pyroxene crystallization and the compositional variation of the parent rocks.

o Chemical analysis of clinopyroxene.

● Chemical analysis of parent rock.

When the ratios for the clinopyroxenes and the parent rocks are compared (Table 1 and Text-fig. 4) the ratio in the pyroxenes is always lower, as might be expected in this isomorphous series, than in the parent rock. They are similar in the picrite and the lowest picrodolerite, but between 37 and 75 feet there is a large increase in the ratio in the rock and a relatively small increase in the ratio in the pyroxene. Thereafter the rates of change of the ratios with height are similar. The ratio in the olivine is greater than that in the pyroxene, and in the upper part of the sill it is greater than the ratio in the parent rock.

The rocks of the Garbh Eilean sill show progressive enrichment in iron oxides and alkalis relatively to magnesia up to a limiting value in the crinanite (Text-fig. 4). The associated pyroxenes are richer than the rocks in magnesia and show progressive enrichment in iron and no

apparent increase in alkalis with advancing crystallization. A few small grains of olivine, of composition Fa_{65}, have been found in the analcite-syenite. The parent rock (SE) has been plotted (Text-fig. 4). A nepheline syenite (W) from Salem Neck and its acmitic hedenbergite (Washington and Merwin, 1927) have been plotted for comparative purposes. The Portrush orthophyre vein shows a higher degree of iron enrichment than the late-stage analcite-syenite of the Shiant Isles.

According to Harris (1937), the olivine-dolerite magma of the Portrush sill has metasomatized and mobilized the contiguous argillaceous sediments and the sill has been injected by the resultant rheomorphic veins. The origin of the orthophyre is referred to such a process. Walker and Poldervaart (1949) have shown that the Karoo dolerite magma " was extremely active towards the associated sedimentary rocks causing widespread syntectic phenomena ". Stoped siltstone blocks have been transformed into granophyre, containing a hedenbergitic pyroxene, from which rheomorphic veins emerge into the dolerite. The process involved an addition of considerable Fe and relatively less Mg and Ca to, and a loss of Si from, the xenolith. The exogenous iron enrichment was followed by enrichment in soda.

The Portrush orthophyre is a perfectly uniform rock. Its formation, although dependent on reciprocal chemical exchange with argillaceous hornfels, seems clearly to have been controlled, as in its granophyre counterparts of tholeiitic parentage, by late-magmatic crystal $\rightleftarrows$ liquid equilibrium. This indication of a late-magmatic convergence to a residuum in which hedenbergitic ferroaugite and fayalitic olivine (ferrohortonolite) are the stable phases suggests an important field for further investigation.

Acknowledgments

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A New Species of *Carbonicola* from near the Base of the Namurian in Ayrshire

By G. M. Bennison

Abstract

The marine Johnstone Shell Bed, an important index horizon in the Limestone Coal Group of the Carboniferous of Scotland, is succeeded in North Ayrshire by a bed containing *Lingula squamiformis* Phillips, and many small shells here referred to a new species of the genus *Carbonicola*. This *Carbonicola* community has been examined in detail, and graphical representation of the great variability has been employed.

Introduction

An investigation of the fauna of the Limestone Coal Group of the Carboniferous in Ayrshire has shown that lamellibranchs of non-marine type occur at two horizons—in the Johnstone Shell Bed and in the Maich Shell Bed. Both shell beds possess special faunas rich in individuals but sparse in genera. It is intended to give a detailed description of both the geographical and stratigraphical distribution of these faunas in a separate paper.

The Johnstone Shell Bed is a well-known marine index horizon found throughout the Midland Valley of Scotland, but here in North Ayrshire, north of the Dusk Water Fault, it is of especial interest for the marine bed is succeeded immediately by a non-marine bed. The total thickness of the shell bed is from 6 to 10 feet of dark bluish-grey mudstone. The lower 4 to 6 feet bear a largely brachiopod and lamellibranch fauna—chiefly productids and *Aviculopecten*—but other marine lamellibranchs and *Bellerophon* are common. Craig (1883, pp. 93–6) has recorded several species from each of the following genera: *Productus*, *Lingula*, " *Rhynchonella*," *Aviculopecten* (many species), *Edmondia*, *Nucula*, *Bellerophon*, *Orthoceras*, Crinoids, and Ostracods.

Most of the above forms were found at all the principal localities where the Johnstone Shell Bed outcrops. While none of the species is of short range the shell bed is easily recognized since it is the only horizon in the Limestone Coal Group with an abundant marine fauna.

The upper part of the Johnstone Shell Bed consists of shaly mudstones, lithologically very similar to those immediately beneath; *Lingula squamiformis* Phillips is found in large numbers, together with a profusion of lamellibranchs here referred to the genus *Carbonicola*. The relationship is not, however, a straightforward one, for at some localities *Carbonicola* is uncommon or absent though *Lingula* abounds, while the converse has not been observed and nowhere do mussels

occur without *Lingula* also being present. The distribution of shells throughout the shell bed—examined by means of inch by inch collection—indicates a further complexity. While *Lingula* increases numerically upwards through the shell bed (except for the top few inches in which fossils are infrequent making the top of the shell bed difficult to define), *Carbonicola* decreases. Thus *Lingula* and *Carbonicola* overlap and may occasionally be seen resting on the same bedding plane. It would appear that the key to the problem of the ecology of the mussels may be found by a study of the ecology of *Lingula*. Important work on the ecology of modern *Lingula* has been done by Yatsu (1902), and on modern and fossil lingulids by Craig (1952) and it has been shown that, whilst *Lingula* is always marine, it has a wider tolerance of variations in salinity than the other animals which share its environment.

The *Carbonicola* and *Lingula* under discussion are not found fossilized in the position of growth. Thus while there is evidence that they co-existed simultaneously—since they occur on the same bedding planes—and they may have shared the same general habitat, it must not be assumed that they shared the same ecological station. Occasionally the valves of *Lingula*, which always occur separately, are fragmented indicating transportation or " washing in ".

Lingula squamiformis Phillips attains a normal size, averaging *c.* 13 mm. measured in an anterior-posterior direction, but the mussels are quite small, having an average length of a little over 13 millimetres. It must not be assumed, however, that they are necessarily a dwarfed fauna before ascertaining whether this species elsewhere attains a larger size. It is possible that their environment was inimical to their growth, since their occurrence in intimate association with *Lingula* is unusual.

With the exception of *Lingula*, marine shells are not found in the upper part of the shell bed and the fauna consists only of *Lingula*, *Carbonicola* and a very few specimens of *Naiadites crassa* (Fleming) such as occur at a number of horizons below the Limestone Coal Group and within the group in the Maich Shell Bed.

The shells are, beyond all doubt, referable to the genus *Carbonicola*, a fact established by their conformity in all the essential features to the definition given by Trueman and Weir (1946, Part 1, p. 2). The nature of the hinge-plate, although not commonly preserved itself, is shown by the beaks, which in moulds are prominent and not contiguous. The lack of dentition in most shells is not at variance with the characteristics of the genus, but where teeth are present they are typical of *Carbonicola*. The growth lines show little tilting and give no evidence of sudden changes in the direction of growth. In some secondary features the shells are seen to be typical of the genus; this is brought out in the description on page 39.

The Carbonicola Community

The *Carbonicola* fauna was sufficiently abundant at four localities for enough material to be obtained to permit a statistical analysis. These were the exposures in Kersland Glen and in Powgree Burn, both near Glengarnock, and near Beith Station and in Paduff Burn, Kilbirnie. The first two of these are shown on Geological six-inch maps as outcrops of the Johnstone Shell Bed: the last two are not, but it has been established that they lie at, or very near to, the horizon of the Johnstone Shell Bed. It was the intention to collect approximately one hundred specimens from each of these localities for the purpose of statistical analysis to ensure reliable results. In the case of the Beith Station and Powgree Burn collections the number of measurable specimens falls slightly short of this figure although in every case more than a hundred shells were examined. Only those shells which would provide apparently reliable measurements were utilized for statistical purposes.

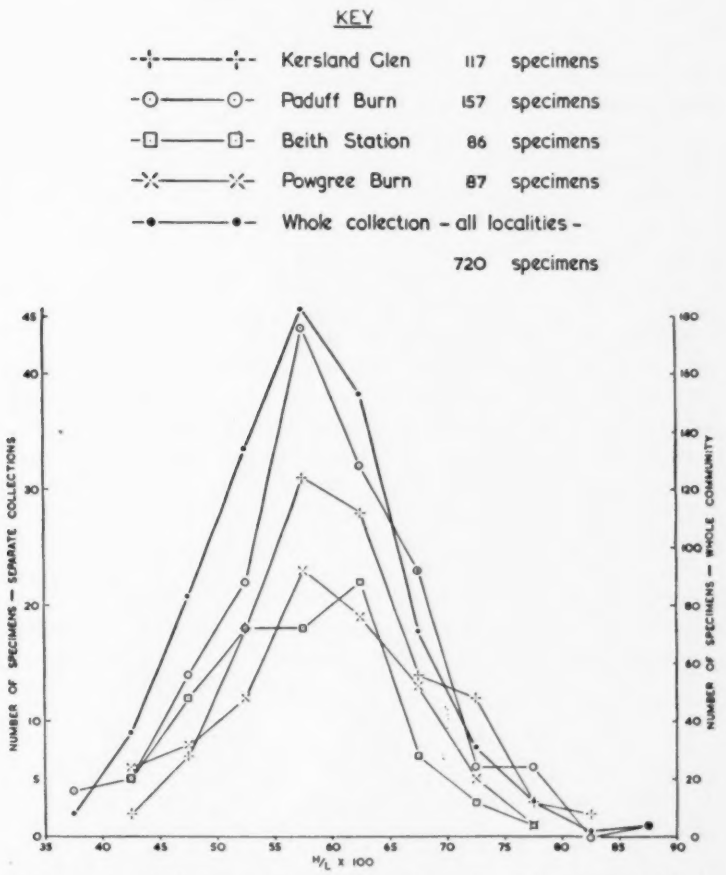
The shells were measured in the standard directions (Davies and Trueman, 1927, p. 212) for L, H, and A. No specimen could be extracted " solid " and in only a few cases could the tumidity be estimated, and then only approximately.

Relatively small (i.e. young) individuals are unaccountably few in number. Fewer than 5 per cent of the total are less than two-thirds the mean length. On the other hand some 2–3 per cent are considerably larger (over 50 per cent greater in length) than the mean of the community. Eagar (1950, pp. 29–31, and 1952, pp. 349–351) has discussed the changes in the ratios of H/L and A/L which occur during growth, but since the dimensions of the majority of the shells are not far removed from the mean value no account has been taken of this effect. The relative scarcity of small shells, accompanied by the fact that small fossils such as Ostracods are very few in number, may be due to sorting by wave-action or currents. The mussels and *Lingula* are of approximately the same size and this could account for their being found together through " washing in ".

Other variable features occur such as the incurvature of the anterior-umbonal slope, the slight inclination of the growth lines to the ventral margin and the oblique downward truncation of the dorsal slope noticeable in some variants, but these are scarcely measurable properties. Such variations are portrayed graphically but they are not subjected to statistical analysis.

Variation diagrams were drawn for the ratio of height to length (H/L) and the ratio of length of anterior end to length (A/L) (expressed as percentages) for the assemblages taken from the four localities mentioned. These curves are shown in Text-figs. 1 and 2.

The range of variation of these ratios is fairly great but is approxi-


KEY
Kersland Glen 117 specimens
Paduff Burn 157 specimens
Beith Station 86 specimens
Powgree Burn 87 specimens
Whole collection - all localities - 720 specimens
NUMBER OF SPECIMENS — SEPARATE COLLECTIONS
NUMBER OF SPECIMENS — WHOLE COMMUNITY
H/L x 100

TEXT-FIG. 1.—Variation graphs to show the ratio of length to height in *Carbonicola* from the Johnstone Shell Bed.

mately the same at each locality. The curves are all unimodal (that is they each show a single maximum) and the modes are similar:—

	Kersland Glen	Powgree Burn	Beith Station	Paduff Burn	All Specimens
H/L × 100	57·5	57·5	62·5	57·5	57·5
A/L × 100	27·5	27·5	22·5	27·5	27·5

The apparently large discrepancies in the figures for the Beith Station collection are entirely a function of the intervals chosen. Since the range of variation is so great it was found necessary to choose

a wide interval between the values of H/L and A/L plotted as abscissae of the graphs. The curves were redrawn choosing different intervals and, though the curves so obtained are not reproduced here, the figures obtained for the modes were:—

	Kersland Glen	Powgree Burn	Beith Station	Paduff Burn
H/L × 100	60	55	60	60
A/L × 100	25	25	30	25

In every case a continuous curve was obtained suggesting that all the members of the *Carbonicola* community belong to one and the same species group. The close similarity of the curves also shows that the community has the same range of variability at all four localities.

In the Paduff Burn exposure the shell bed is so well developed and exposed that it was possible to make separate collections from the top, middle, and base of the shell bed for comparison. Samples were taken from three six-inch bands. Variation diagrams for H/L and A/L expressed as percentages were drawn and compared with curves obtained for the summation of all three samples, as well as for a representative collection made from the whole 4 ft. 6 in. of the shell bed. The modes of the curves were as follows:—

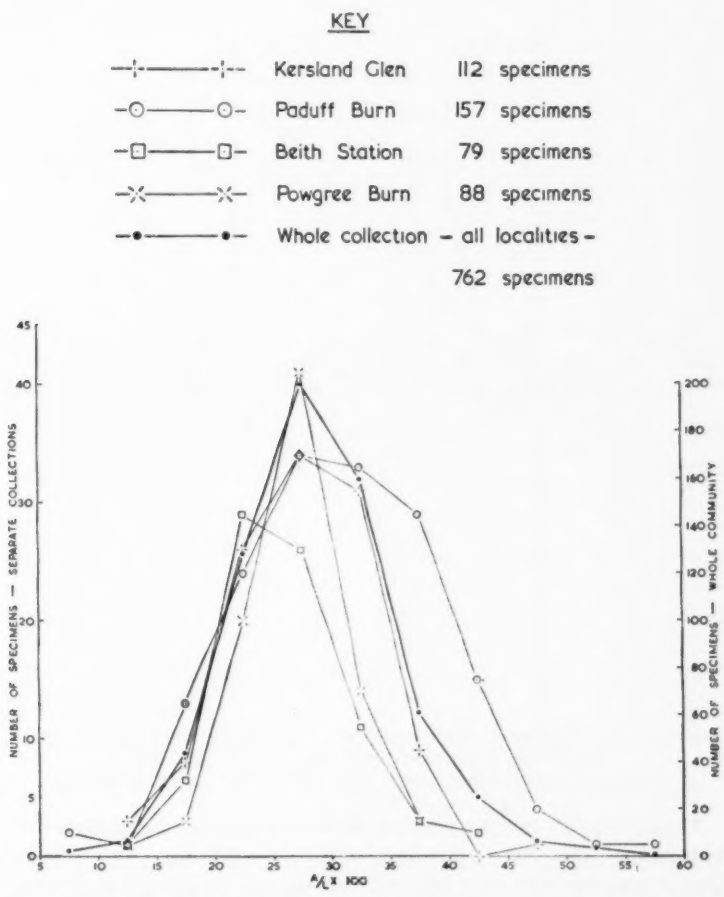
	Samples from			Summation	Whole Community
	Base	Middle	Top		
H/L × 100	57·5	52·5	57·5	57·5	57·5
A/L × 100	27·5	32·5	32·5	32·5	27·5

The graphs were re-drawn choosing different intervals for the abscissae, but in every case the modes of the A/L curves were higher for the samples from the middle and top of the shell bed than for the sample from the base. This apparently indicates that there is some slight trend of variation with horizon in this, admittedly very limited, example.

Since the community is distinct when considered as a whole it is proposed that these shells shall be assigned to a new species, *Carbonicola pervetusta*, of which a full description is given below. The name is used throughout the following discussion.

The factors involved in the variation of shell shape are:—

(*a*) Relative elongation (or decrease in height): the height varies between 39 per cent and 87 per cent of the length with a mode between 55 per cent and 60 per cent (approximately 57·5 per cent).


KEY
Kersland Glen 112 specimens
Paduff Burn 157 specimens
Beith Station 79 specimens
Powgree Burn 88 specimens
Whole collection – all localities –
762 specimens
NUMBER OF SPECIMENS – SEPARATE COLLECTIONS
NUMBER OF SPECIMENS – WHOLE COMMUNITY
L x 100

TEXT-FIG. 2.—Variation graphs to show the ratio of length to length of anterior end in *Carbonicola* from the Johnstone Shell Bed.

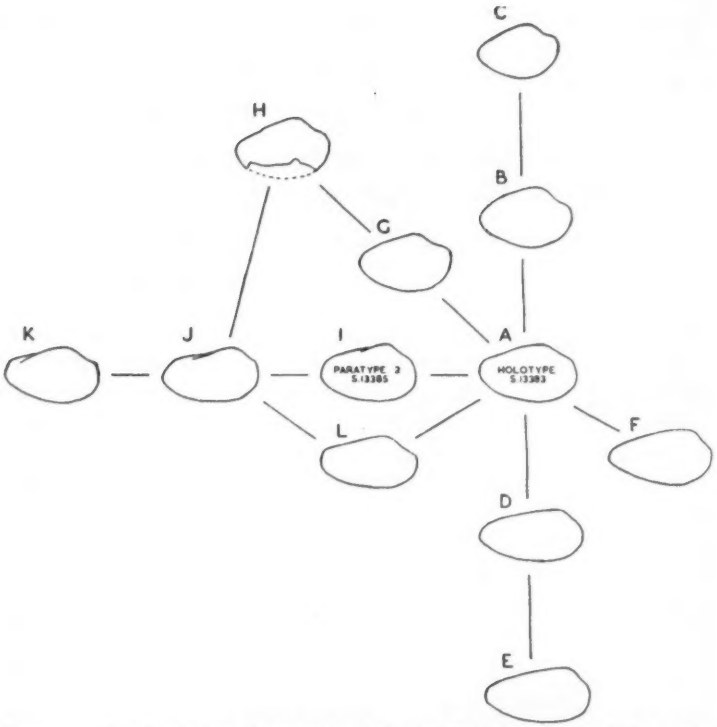
(*b*) Variation in the position of the umbo so that the length of the anterior end varies between 10 per cent and 50 per cent of the length with a mode between 25 per cent and 30 per cent (approximately 27·5 per cent).

(*c*) Changes in the degree of curvature of the ventral margin.

(*d*) Incurvature of the anterior-umbonal slope.

(*e*) Oblique truncation of the posterior margin.

(*f*) An increasing tendency for the dorsal margin to become arched near to the posterior end.

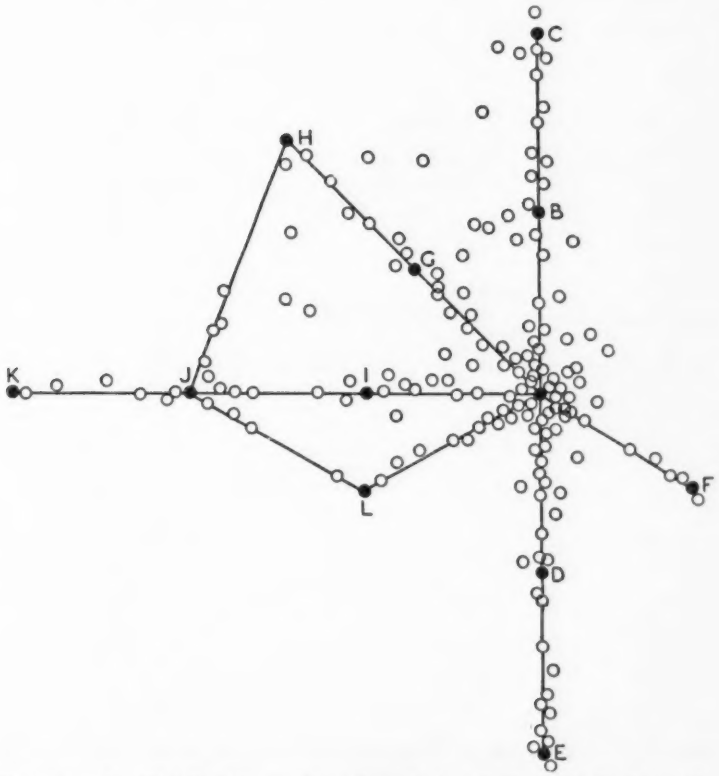


TEXT-FIG. 3.—Variation intergrades of *Carbonicola* arranged in series. From the Johnstone Shell Bed, Kersland Glen.
All shells drawn as right valves and reduced to the same height.

Certain factors causing shape variation show some degree of correlation in that they vary in conjunction with one another. Thus elongation is accompanied by a tendency for the ventral margin to become straighter. The incurvature of the anterior-umbonal slope is more pronounced in those shells with a relatively long anterior end (with a high value for A/L).

Thus the variants resulting from combinations of such changes can be arranged in series illustrating their nature and degree of variation from the norm of the community.

Text-fig. 3 is an arrangement on a morphological basis of the variants into series of transitional intergrades (cf. Leitch, 1936, and Eagar, 1947), and Text-fig. 4 shows the distribution of the community relative to the figured intergrades of Text-fig. 3. Text-fig. 5 summarizes the main changes shown by the figured intergrades. The greatest concentration of specimens is, of course, centred about the norm for the norm is very close to the mode. The distribution of the community above



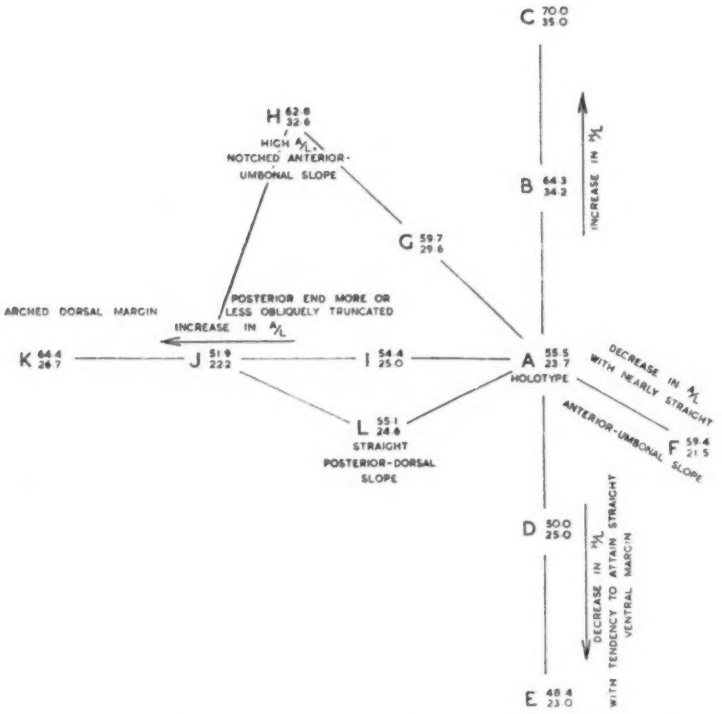
TEXT-FIG. 4.—Distribution scatter of variants of *Carbonicola* from the Johnstone Shell Bed, Kersland Glen.
Lettered circles represent the figured intergrades of Text-fig. 3.

and below the norm in Text-fig. 4 is almost symmetrical but rather more specimens lie to the left of the norm than to the right, since variants with a high value for A/L are relatively more numerous.

DESCRIPTION

Carbonicola pervetusta sp. nov.

Diagnosis.—Small, ovate, showing considerable variation in shell shape. Height typically 50–60 per cent of the length. Postero-dorsal margin slightly concave and, rarely, arched near to the posterior end. Posterior end is bluntly rounded though sometimes obliquely truncated. The ventral margin is gently rounded and passes upwards in a continuous curve to the anterior end which is moderately short (*c.* 27 per cent of the length). Anterior-umbonal slope slightly concave. Growth lines, which are very faint, are parallel to the ventral margin or very slightly inclined.



TEXT-FIG. 5.—Variation of characters shown by the figured specimens of Text-fig. 3.

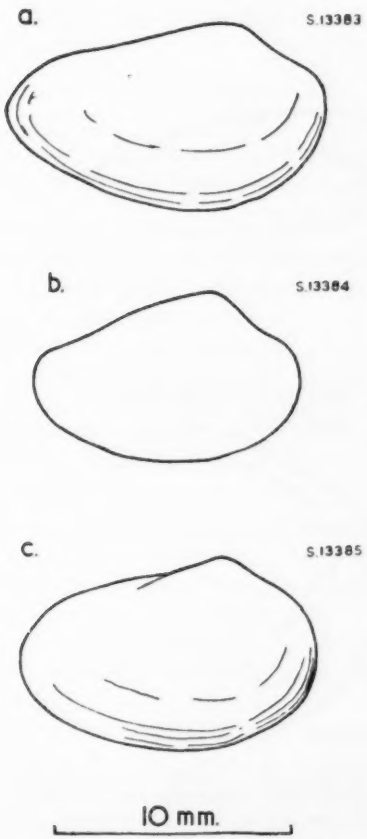
Dimensions.—

	Length. mm.	*Height.* mm.	*Anterior end.* mm.
Holotype (S. 13383) . .	13·7	7·6 (55·5%)	3·25 (23·7%)
Paratype 1* (S. 13384) . .	11·2	6·7 (59·8%)	3·3 (29·5%)
Paratype 2 (S. 13385) . .	13·6	7·4 (54·4%)	3·4 (25·0%)
Paratype 3 (S. 13386) . .	13·4	8·5 (63·7%) estimated	5·2 (38·1%)

Means of the community: L, 13·58 mm., H, 8·33 mm., A, 4·05 mm.
Modes of the community: H/L, 57·5%, A/L, 27·5%.
(* Internal measurements.)

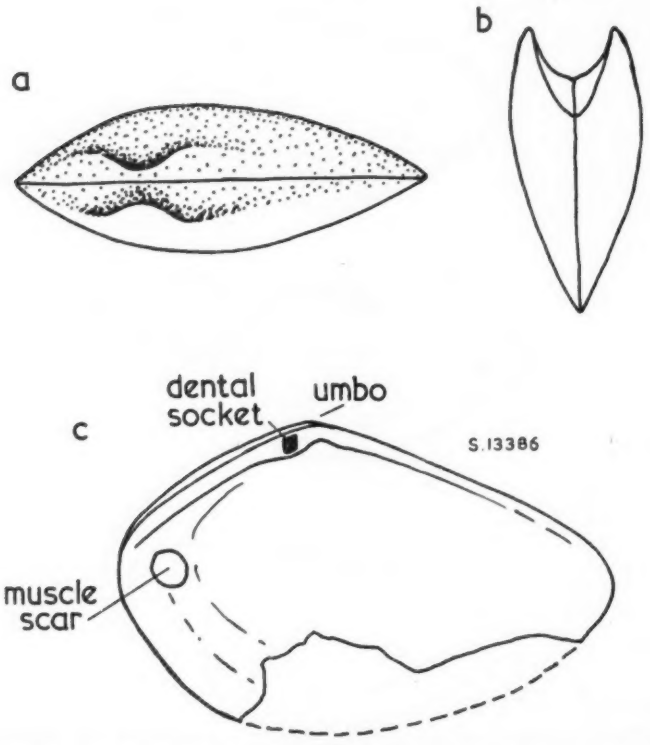
Registration numbers preceded by letter S refer to the Hunterian Museum collection, Glasgow.

Description.—In addition to length, height, and length of anterior end, the tumidity may sometimes be estimated, although the only material obtainable is single valves; in no case was it possible to extract a shell "solid". The maximum tumidity occurs at one-third of the height below, and just posterior to, the umbones (Text-fig. 7*a* and *b*).



TEXT-FIG. 6.—Holotype (S. 13383) and Paratypes 1 (S. 13384) and 2 (S. 13385) of *Carbonicola pervetusta* sp. nov., from the Johnstone Shell Bed of Kersland Glen.

The growth lines, always faint, are often not discernible since some shell material has been eroded away. In some cases the greater part of the shell material has been removed and these specimens are not included in the statistical analysis. Teeth are absent in nearly every case but not all specimens are edentulous. Plasticine impressions of the umbonal region of more than twenty better preserved shells failed to provide any evidence of dentition. In a single specimen, paratype 3 (S. 13386) (Text-fig. 7*c*), there is a single cardinal dental socket situated just anterior to the umbo. It is deep, extending almost to the base of the hinge plate. The latter is not complete but there is no evidence of lateral teeth. The development of a large dental socket must be assumed to be exceptional in this community and the hinge is usually edentulous,



TEXT-FIG. 7.—Internal characters of *Carbonicola pervetusta* sp. nov., from the Johnstone Shell Bed, Kersland Glen. Text-fig. 7*c* is Paratype 3 (S. 13386). Figures (*a*) and (*b*) are restorations of internal moulds. × 5.

in contrast with the great variety of dentition found in *Carbonicola* from higher horizons, for example those hinge structures described by MacLennan (1944).

Carbonicola pervetusta is perhaps more closely related to the small forms from the Lenisulcata zone described by Eagar (1946, p. 7) in which, as he says, " Deviations, swellings, and depressions of the hinge plate are much more common than are small teeth," and some shells " . . . appear quite edentulous ". Muscle impressions are not commonly seen despite the frequency of internal moulds, but the anterior adductor impression may be clearly seen in a few better preserved specimens, and apparently it may have had a deep insertion in the shell. The pallial line appears to be entire.

Comparison.—Both *Carbonicola antiqua* Hind *non* Brown (Hind, 1894, Pt. I, Plate xi, figs. 28, 29) and *Carbonicola elegans* (Kirby)

(Hind, 1895, Pt. II, Plate xx, figs. 13, 15) fall within the range of variation exhibited by *C. pervetusta*.

		H/L	A/L
Carbonicola pervetusta	Modes:	57·5%	27·5%
	Ranges:	39–87	13–47
C. antiqua (Hind Pl. xi, fig. 28) (L. 46889)		63·7%	22·8%
,, (Hind Pl. xi, fig. 28) (L. 46890)		67·8%	21·5%
C. elegans (Hind Pl. xx, fig. 13) (L. 47163)		41·4%	19·3%
,, (Hind Pl. xx, fig. 15) (L. 47164)		50·3%	19·7%

N.B.—Registration numbers preceded by letter L refer to specimens in the collections of the British Museum (Nat. Hist.). (Ratios for *C. antiqua* Hind *non* Brown and *C. elegans* (Kirby) calculated from measurements made of type specimens.)

In shape of outline both *C. antiqua* and *C. elegans* are not unlike certain more extreme variants of *C. pervetusta*, and the type specimens of the first two specimens could be fitted into Text-fig. 4. It is, however, only in shape of outline that the Calciferous Sandstone forms bear a resemblance to *C. pervetusta*: the similarity is superficial. The following significant differences have been noted:—

(1) Both *C. antiqua* and *C. elegans* possess curved umbones directed downwards and in a posterior direction.

(2) In both species growth lines are conspicuous and greatly tilted.

(3) Both species are much more tumid than *C. pervetusta*, and *C. antiqua* might be described as inflated. The robustness of the shells of *C. antiqua* and *C. elegans* is not fully apparent from Hind's plates (op. cit.).

(4) The anterior end in the case of both *C. antiqua* and *C. elegans* is rather shorter than is commonly found in *C. pervetusta*.

(5) Almost all the shells of *C. pervetusta* are smaller than *C. antiqua* and *C. elegans*. The mean length of the Johnstone Shell Bed community is 13·5 mm. compared with lengths of 23·7 mm. and 24·6 mm. for the type specimens of *C. antiqua*, and 18·1 mm. and 19·7 mm. for the type specimens of *C. elegans*.

(6) The umbones in *C. antiqua* are contiguous.

Brown (1843, Plate xvi, fig. 1) figured a new species *Carbonicola* (*Pachyodon*) *nucleus* from the Calciferous Sandstone at Woodhall, which lies midway between Colinton and Currie, south-west of Edinburgh. It is apparent from his figure that *C. nucleus* is synonymous with *C. antiqua* which occurs at about the same horizon in Fife (in the latter approximately 3,000 feet below the Hurlet Limestone). Hind (1894, pp. 63 and 80) alludes to *C. nucleus* and says: "It is very possible that it and the species under discussion (*C. antiqua*) are the same." It seems advisable that the use of name *antiqua* should be discontinued since it is possibly a synonym. It seems probable that *C. pervetusta* from the Limestone Coal Group may stand as a

transitional form between the two Calciferous Sandstone species and certain species of *Carbonicola* from the Westphalian Coal Measures. The similarity of *Carbonicola venusta* Davies and Trueman from the Modiolaris Zone to *C. pervetusta* has been pointed out to me by Dr. Weir and some variants of the two species may be homoeomorphic.

Distribution.—*C. pervetusta* is found only at one horizon, the upper part of the Johnstone Shell Bed of the Limestone Coal Group, and so far it has been discovered only in North Ayrshire, at eight exposures.

ACKNOWLEDGMENTS

The writer would like to express his thanks to Dr. J. Weir for reading the manuscript and making many useful suggestions. Thanks are also due to Dr. W. Hopkins for helpful advice and criticism, and to Officers of H.M. Geological Survey for permitting access to the collections in their care.

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The Structure of the Plastron of the Echinoid *Somaliaster* Hawkins

By Kenneth A. Joysey

Abstract

Previous descriptions of the plastron of *Somaliaster* Hawkins have been conflicting and, in consequence, there has been some doubt regarding the systematic position of this genus. The type-material has been re-examined and the plastron found to be meridosternous. *Somaliaster* is here referred to the family *Stenonasteridae*, where it has close affinities with *Iraniaster* Cotteau and Gauthier.

Previous Work

THE genus *Somaliaster* was erected for the reception of a new echinoid species, *Somaliaster magniventer* Hawkins (1935), described from the Upper Senonian (?) of British Somaliland. Maccagno (1941) redescribed this species on the basis of new material from Italian Somaliland and also described *Somaliaster magniventer* var. *checchiai* as a new variety. In general, these previous descriptions have been so accurate in detail that further comment here is unnecessary; but they do not agree with one another regarding the structure of the plastron.

In describing the plastron Hawkins (1935) stated: "The plastron, which is enormously inflated in the large specimens, consists of a single proximal plate extending about half the distance between the peristome and the periproct, followed by two columns (? amphisternous)." He also commented: "There is no definite labrum, but the inflated plastron may give the effect of one."

Maccagno's (1941) description (translated from Italian) states: "The labrum is protuberant, posteriorly it is in contact with the large sternal, which occupies about half the distance between the peristome and periproct. The large sternal, in its turn rests upon two plates, so that one has: the labrum, a single large sternal, two episternals, and therefore the plastron is orthosternous. In nearly all the specimens the mouth is broken and this explains how it is that Hawkins, in his description of *Somaliaster*, denies the existence of the labrum. However, even in many specimens with a badly preserved peristome, one can distinguish traces of the labrum."

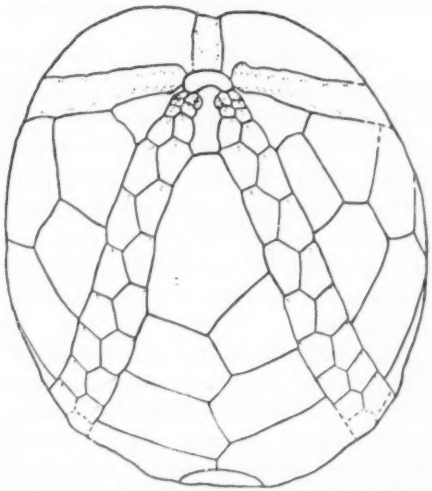
In his *Monograph of the Echinoidea* Mortensen (1950), threw doubt on these descriptions: "The structure of the plastron, if correctly described, would show it [*Somaliaster*] to belong to the *Meridosternata*; but I do not feel at all convinced that the description and illustrations given by Maccagno are correct—and I do not see to which family of the *Meridosternata* it could belong."

Since the plastron is of primary importance in classification it is

desirable that its structure should be completely known. In consequence, the writer has re-examined Hawkins's original material, which consists of four cotypes and fifteen topotype specimens, in the Sedgwick Museum, Cambridge.

Description

The complete arrangement of plates on the oral surface can be observed in specimen F. 152 (Text-fig. 1), and also in two other



Text-fig. 1.—The oral surface of *Somaliaster magniventer* Hawkins. Sedgwick Museum, No. F. 152. × 1½.

specimens, F. 165 and F. 167, which agree in all essential details. The labrum (labral plate) extends from the border of the peristome to the anterior end of the fifth ambulacral plate on either side. The length of the labrum is about three times its maximum width and its sides are scalloped to receive the adjoining ambulacral plates, which are crowded in the region of the peristome. The anterior border of the labrum extends a short distance over the peristome forming a slight lip. It seems likely that some of the previous confusion regarding the existence of the " labrum " is due to this same term being employed to refer to both the " labral plate " and to the " lip ".

Posteriorly the labrum is in contact with a single large sternal plate, so there is no doubt that the plastron of *Somaliaster* is meridosternous. This sternum extends posteriorly to a position about half of the total distance from the peristome to the periproct. Its total length is about one and a half times its maximum width, but it is

asymmetrical and extends further posteriorly on the side adjoining ambulacrum I. The sternum is followed by a double series of plates. The most anterior of these, which abuts against the end of the sternum on its shorter side, is quadrangular in shape, whereas all the other plates are pentagonal.

It is of interest to note that interambulacrum 4 is amphiplacous, whereas interambulacrum 1 is meridoplacous in structure. This peculiarity has been confirmed on several specimens and is particularly well shown by F. 167.

The primary perforate tubercles which have previously been described as apparently non-crenulate, are in fact crenulate, but this can only be observed around patches of adherent matrix, where the surface is unweathered.

The apical disc of *Somaliaster* is generally ethmophract, but as the madreporite plate penetrates between the posterior oculars to a varying degree, in the extreme case it becomes ethmolytic as an individual variation.

The Affinities of Somaliaster

In discussing the possible affinities of *Somaliaster*, Hawkins (1935) compared and contrasted the characters with those of *Holaster* L. Agassiz, *Cardiaster* Forbes, *Isomicraster* Lambert, *Macraster* Roemer, *Palhemiaster* Lambert, *Lambertiaster* Gauthier, and *Enallopneustes* Pomel. Finally, he concluded that the new genus should be referred to the family *Hemiasteridae*.

Maccagno (1941) stated that *Somaliaster* could not belong to the *Hemiasteridae*, or to any family within the *Brissidae* as the lateral ambulacra are not deeply sunken. Instead, comparison was made with *Antillaster* Lambert, *Mokotibaster* Lambert, and *Pharaoaster* Lambert, and finally *Somaliaster* was referred to the *Antillasterinae* (= *Palaeopneustidae*).

Mortensen (1950) joined Hawkins in referring *Somaliaster* to the *Hemiasteridae*, though he expressed " serious doubts as to its real classificatory position ".

In accordance with Mortensen's (1950) classification, *Somaliaster* must be excluded from both the *Hemiasteridae* and the *Palaeopneustidae*, on account of the meridosternous structure of the plastron. Amongst the *Meridosternata*, *Somaliaster* cannot be included within either the *Holasteridae* or the *Urechinidae* as both of these families are characterized by an intercalary apical disc. Furthermore, the *Urechinidae*, like the *Pourtalesidae* and the *Calymnidae*, possesses uniporous ambulacra. It seems that the affinities of *Somaliaster* must be sought amongst the diverse group of genera included in the *Stenonasteridae*.

Within the *Stenonasteridae*, *Somaliaster* can be most closely compared with *Iraniaster* Cotteau and Gauthier. Both genera possess a peripetalous fasciole, which is situated just beyond the ends of the petals, and might equally well be described as a marginal fasciole. In *Iraniaster morgani*, the type-species of the genus, interambulacrum 5 is often interrupted by ambulacra I and V which join in the mid-line, so separating the labrum from the sternum. All intermediate stages occur between the interrupted and the normal condition, but the interrupted condition is more common in the large individuals. In its general form, and in the structure of the plastron, *Somaliaster* can be most closely compared with *Iraniaster douvillei*, in which the interrupted condition of the plastron does not occur. Judging from Cotteau and Gauthier's (1895) figures, the oral surface of *Iraniaster douvillei* differs from *Somaliaster*, in that the pores of ambulacra I and V are situated near the posterior border of the plates, and that both interambulacra 1 and 4 are amphiplacous. Cotteau (1902) recognized and discussed the similarities of *Iraniaster* to *Stenonaster*, the type genus of the family.

In conclusion, it is opportune to record the occurrence of *Somaliaster magniventer* from the south-west flank of Kuh-i-Kossamas, Iran, in rocks of Senonian age. The specimens were originally in the collections of the Iraq Petroleum Company, Limited, and have been presented by them to the British Museum (Natural History), where they are registered under the numbers E. 40573–4.

I should like to express my gratitude to Professor H. L. Hawkins for his criticism of the manuscript, to Professor W. B. R. King for the generous provision of research facilities in his Department, and to the Iraq Petroleum Company for access to their records.

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Petrofabric Analyses of the Loch Tay Limestone from Strachur, Argyll

By Paul Gilmour and Max F. Carman

Abstract

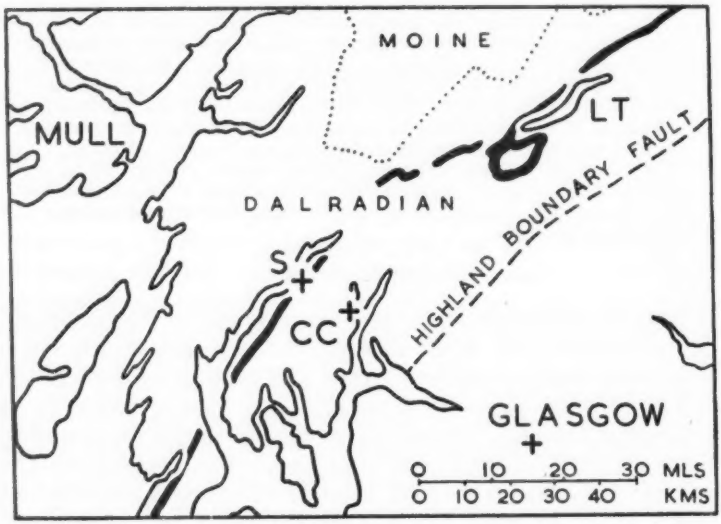
The paper records the results of petrofabric analyses of four specimens of marble from the South-West Highlands of Scotland. The marble fabric has a high degree of homogeneity. Calcite grains are flattened in the foliation plane and are elongate in a direction normal to the fold axis. The *c* crystal axes lie in a distinct girdle about *b*, with a maximum near the pole of the foliation; the *a* crystal axes tend to occupy three maxima, one of which is close to *b*. Late twinning has occurred on $\{01\bar{1}2\}$ apparently in response to a simple stress system, operating in the *ac* plane. The symmetry of the general calcite fabric, the twinning and the megascopic structures coincide.

Introduction

In the course of study of the Cowal area in the South-West Highlands of Scotland, one of the authors [P. G.] is making petrofabric analyses of several of the rock types. This paper records the results of joint work on the fabric of the Loch Tay Limestone (marble) at a locality in this area. The procedure adopted for the measurements is that described by Turner (1949), and an attempt has been made to interpret the fabric in the light of experimental work (Handin and Griggs, 1951 ; Turner, 1953). It is hoped that the study of the fabric of this marble will contribute to the interpretation of petrofabric data derived from other rocks in Cowal and add to the published descriptions of naturally deformed marbles for comparison with the fabrics of artificially deformed rocks. Four specimens, collected within 30 yards of one another, have been studied in order to test the homogeneity of the fabric on this scale.

The analysed specimens were collected from a disused quarry in the Loch Tay Limestones at Glensluan, about one mile south of Strachur, Argyll. The locality map (Text-fig. 1) is the south-westward continuation of the map published by McIntyre and Turner (1953). The Boyne Marble, described by Turner (1953, pp. 277–283), is from a locality on the southern shore of the Moray Firth, approximately 10 miles east of the Moine-Dalradian junction. Comparison of these maps shows that the Scottish marbles so far studied belong to the same general group of regionally metamorphosed limestones. At Glensluan the Loch Tay Limestone is associated with a varied assemblage of metamorphic rocks including phyllites, quartzose schists, and epidiorites. This locality is on the north-west limb of the Cowal "anticline" and the regional foliation dips at approximately 20° to the north-west.

In each of two specimens (Nos. 2 and 3), collected about 30 yards apart, 100 calcite grains were measured in traverses across sections cut normal to the regional lineation and fold axis. In two other specimens (Nos. 1 and 4), collected between the other two, twenty twinned calcite grains were measured.



TEXT-FIG. 1.—Locality map. C C, Carrick Castle; L T, Loch Tay; S, Strachur. The outcrop of the Loch Tay Limestone is shown by the heavy black line. The marbles described were collected about 1 mile south of Strachur.

GENERAL CHARACTER OF THE FABRIC

In Glensluan quarry the rock is a dark coloured calcite marble, with accessory amounts of quartz and mica. A prominent foliation is marked by the parallelism of tabular calcite grains, thin micaceous layers, and quartzose lenses. This foliation was selected as the *ab* plane of the fabric. The *b* fabric axis was taken as parallel to a lineation seen in micaceous laminae ; this direction is parallel to the regional fold axis, which plunges very gently to the south-west.

Field data are :—

Foliation, *ab*—strikes N. 40° E., dips 20° to N.W.
Lineation, *b*—plunges 5° to S.W. at 235°.

In the specimens described there is no evidence of post-crystalline granulation ; the grain boundaries are sharp and strain extinction is almost absent. Most grains possess $\{01\bar{1}2\}$ lamellae and a few show $\{10\bar{1}1\}$ cleavages. These planes were identified by their angular and

zonal relationships. The mean intercepts of the grains parallel to the fabric axes were determined in each specimen by measuring the lengths of traverses required to cross fifty grains in sections respectively parallel to *ac* and *bc*. In each section two to eight traverses were made parallel to each of the two fabric axes. The results are shown in the adjoining Table. The grains are flattened in the foliation plane and have a

TABLE

Specimen.		Dimensions in millimetres parallel to the fabric axes: (*a*)	(*b*)	(*c*)
No. 1	Range of dimensions	0·36–0·47	0·27–0·45	0·15–0·21
	Average dimension	0·41	0·36	0·17
	No. of grains measured	(450)	(260)	(200)
No. 2	Range of dimensions	0·35–0·61	0·29–0·35	0·14–0·18
	Average dimension	0·41	0·31	0·16
	No. of grains measured	(1,300)	(600)	(650)
No. 3	Range of dimensions	0·38–0·54	0·32–0·34	0·14–0·20
	Average dimension	0·43	0·33	0·17
	No. of grains measured	(450)	(250)	(400)
No. 4	Range of dimensions	0·34–0·37	0·33–0·39	0·19–0·24
	Average dimension	0·36	0·38	0·20
	No. of grains measured	(250)	(300)	(350)

slight elongation parallel to *a*; by examination of a section parallel to *ab* in Specimen 2, it was verified that the elongation is in the *a* direction and not in a direction between *a* and *b*. The calcites of previously described marbles are elongate parallel to *b* (e.g. McIntyre and Turner, 1953). In the Cowal Memoir, however, Clough recorded the elongation of large calcite grains in a marble exposure only four miles south-south-west of Strachur as being at right angles to the fold axis (Clough, 1897, p. 46).

Clough mapped faint lineations, approximately normal to the fold axis, all over the Cowal area, and these seem to be the only *a* lineations at present known in the Scottish Highlands, apart from those in the immediate neighbourhood of the great thrusts (McIntyre, 1951, p. 20). Clough undoubtedly recognized that the great majority of small folds, mica crenulations, and similar megascopic *b* structures are parallel to the regional fold axis (Clough, 1897, pp. 24, 25, 87). This interpretation was apparently so obvious to him that, like many of the early Alpine geologists, he recorded the fact, but did not emphasize it. Hence the prevalence and significance of the *b* structures in Cowal was not realized by many geologists. Clough's influence on the progress

of Highland geology was great, and it seems that elsewhere in the Highlands some workers, attempting to follow Clough's lead, but misunderstanding his work, mistook the common *b* structures for the rarer *a* lineations.

Preferred Orientation of the Calcite Lattice

The distribution of *c* axes obtained from both analyses of 100 grains (Nos. 2 and 3) are shown in Text-figs. 2 (*a*) and (*b*). Their close similarity is a measure both of the reliability of the 100-grain samples and of the homogeneity of the fabric over a distance of 30 yards. The *c* crystal axes show a maximum distinctly oblique to the pole of the foliation, with an incomplete but distinct girdle about *b*. Between 60 per cent and 70 per cent of the *c* axes lie at angles greater than 40° to the foliation.

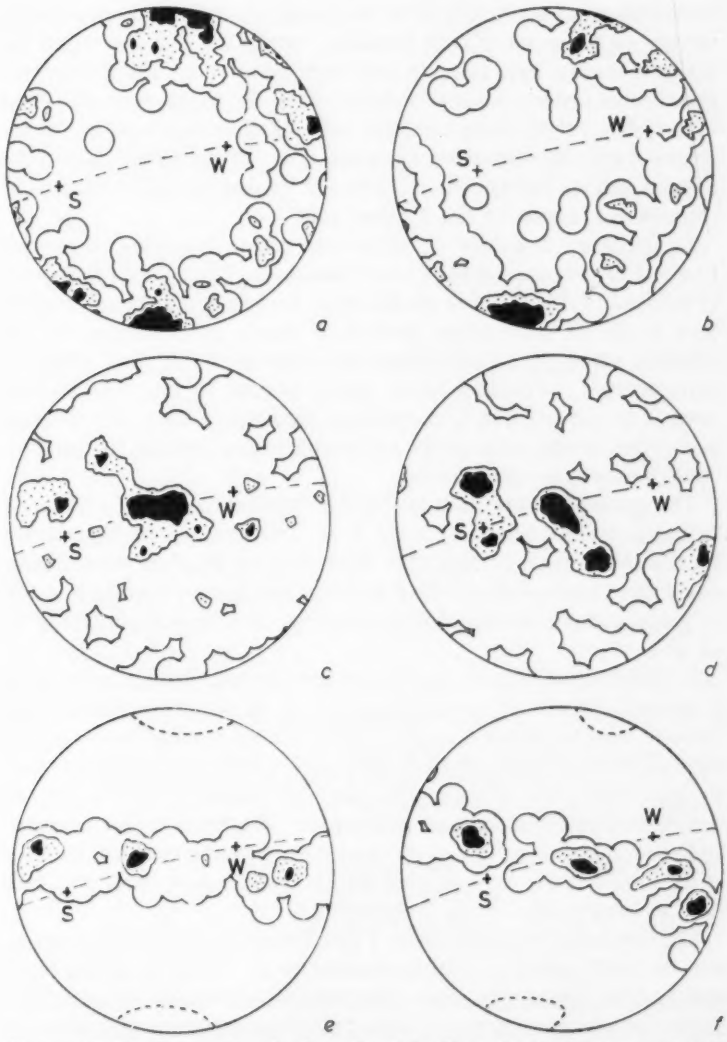
The distribution of *a* crystal axes is restricted by the *c* axis pattern. All *a* axes for the 100-grain analyses are shown in Text-figs. 2 (*c*) and (*d*). In both rocks there is a weak preferred orientation of the *a* axes in three maxima, approximately 60° apart ; one of these maxima coincides with the *b* fabric axis. This distribution might be the consequence of the *c* axis pattern or it might represent a real preferred orientation of the *a* axes. To test this the *a* axes of those grains whose *c* axes fall in the chief maxima shown in Text-figs. 2 (*a*) and (*b*) have been plotted (Text-fig. 2 (*e*) and (*f*)). The majority of these *a* axes must lie in a girdle normal to the *c* axis maximum ; but in both rocks, within the girdles there are three maxima approximately 60° apart, and in each case one of these is nearly parallel to the *b* fabric axis. The reality of the preferred orientation of the *a* axes is thus confirmed.

Preferred Orientation of $\{01\bar{1}2\}$ Lamellae

Approximately 55 per cent of the calcite grains possess three sets of visible lamellae parallel to $\{01\bar{1}2\}$; about 30 per cent possess two sets and 10 per cent one set ; in 5 per cent no lamellae were seen. As less than 3 per cent of the lamellae were inaccessible, these figures are not substantially affected by the " blind spot " of the universal stage. As would be expected from the distribution of *c* axes the best-developed $\{01\bar{1}2\}$ lamellae lie in an *ac* girdle. The edges [e : e′] between pairs of prominent lamellae show a diffuse maximum parallel to *b*.

Twinned $\{01\bar{1}2\}$ Lamellae

Optically recognizable twinning on $\{01\bar{1}2\}$ is not prominent in any of the four specimens analysed. In Specimen 3, 24 per cent of the grains are recognizably twinned, but in the other three specimens only about 4–5 per cent are twinned. The $\{01\bar{1}2\}$ twin lamellae are



TEXT-FIG. 2.—Strachur marble. Specimens 2 and 3. Plane of projection is normal to the lineation as measured in the field. Foliation is left and right; the top is the normal to the foliation in an upward direction. South and west and the horizontal plane are shown. All projections are lower hemisphere.

(*a*) Sp. 2. 100 *c* axes in calcite. Contours 1–3–5 per cent per 1 per cent area.
(*b*) Sp. 3. 100 *c* axes in calcite. Contours 1–3–5 per cent per 1 per cent area.
(*c*) Sp. 2. 300 *a* axes in calcite. Contours ½–2–3 per cent per 1 per cent area.
(*d*) Sp. 3. 300 *a* axes in calcite. Contours ½–2–3 per cent per 1 per cent area.
(*e*) Sp. 2. 60 *a* axes of all twenty grains whose *c* axes occupy the area within the broken lines. Contours 1½–7–10 per cent per 1 per cent area. Highest concentration is 12 per cent per 1 per cent area.
(*f*) Sp. 3. 48 *a* axes of all sixteen grains whose *c* axes occupy the area within the broken lines. Contours 2–6–10 per cent per 1 per cent area. Highest concentration is 12 per cent per 1 per cent area.

invariably narrow. Nearly all of the grains showing obvious twinning possess only one set of twin lamellae ; about 1–2 per cent of all the grains measured have two. In both sections in which 100 grains were investigated systematically a number of twinned grains were measured in addition ; these latter conform with the conclusions based on the results from the systematic traverses. In the remaining two rocks (Nos. 1 and 4) twenty twinned grains were selected and measured in sections cut normal to the *b* fabric axis.

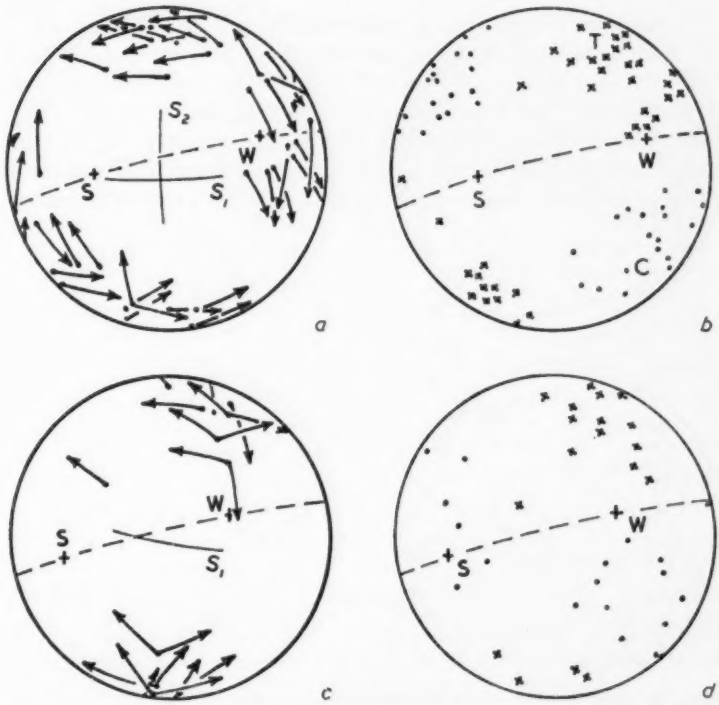
In Specimen 3, a total of thirty-four grains, including three with two sets of twinned lamellae, were measured. Their *c* axes and poles of twinned $\{01\bar{1}2\}$ lamellae are shown in Text-fig. 3 (*a*). These lamellae tend to be oriented either parallel or nearly perpendicular to the foliation plane *ab*. They define two *s*-planes of the final phase of deformation ; s_1 parallel to *ab* and s_2 normal to *ab*. The *s*-plane normal to the foliation is particularly significant, since only a small proportion of the calcite grains are oriented so as to allow twinning on $\{01\bar{1}2\}$ normal to the foliation.

The applied stresses most favourably oriented to effect the observed twinning are shown in Text-fig. 3 (*b*) (Handin and Griggs, 1951, pp. 866–9 ; Turner, 1953, p. 282). In every grain the observed twinning could have been produced by a simple stress system operating in the *ac* plane, either a compression parallel to C or a tension parallel to T, or both.

In Specimen 2, twelve grains with narrow but distinct twins were measured, five of these grains have two sets of twinned lamellae. The twinned lamellae define a single *s*-plane, almost parallel to the megascopic foliation, i.e. parallel to s_1 (Text-fig. 3 (*c*)). This was confirmed by the observation of only one distinctly twinned grain in an *ab* section containing more than 400 grains. The fields of compression and tension giving maximum resolved shear stress on twinned lamellae in the direction and sense of twin gliding coincide with those obtained for Specimen 3 (cf. Text-fig. 3 (*b*) and (*d*)).

The remaining specimens (Nos. 1 and 4) were analysed by measuring only twinned grains in sections normal to *b*. Twinned grains were searched for carefully in areas containing 500–600 calcite grains. The slides were rotated in the universal stage to minimize the effect of using only one section, and as many twinned grains as possible were measured. Twenty twinned grains were recorded in each section, several having two sets of twinned lamellae. In both these rocks the twinned lamellae lie at high angles to the foliation, i.e. parallel to s_2 (Text-fig. 4 (*a*) and (*c*)). The compression and tension points are grouped in fields which correspond closely with those obtained from the 100-grain analyses of the other two specimens.

Points representing the centres of the fields of compression and



TEXT-FIG. 3.—Strachur marble. [Specimens 2 and 3. Orientation as in Text-fig. 2.

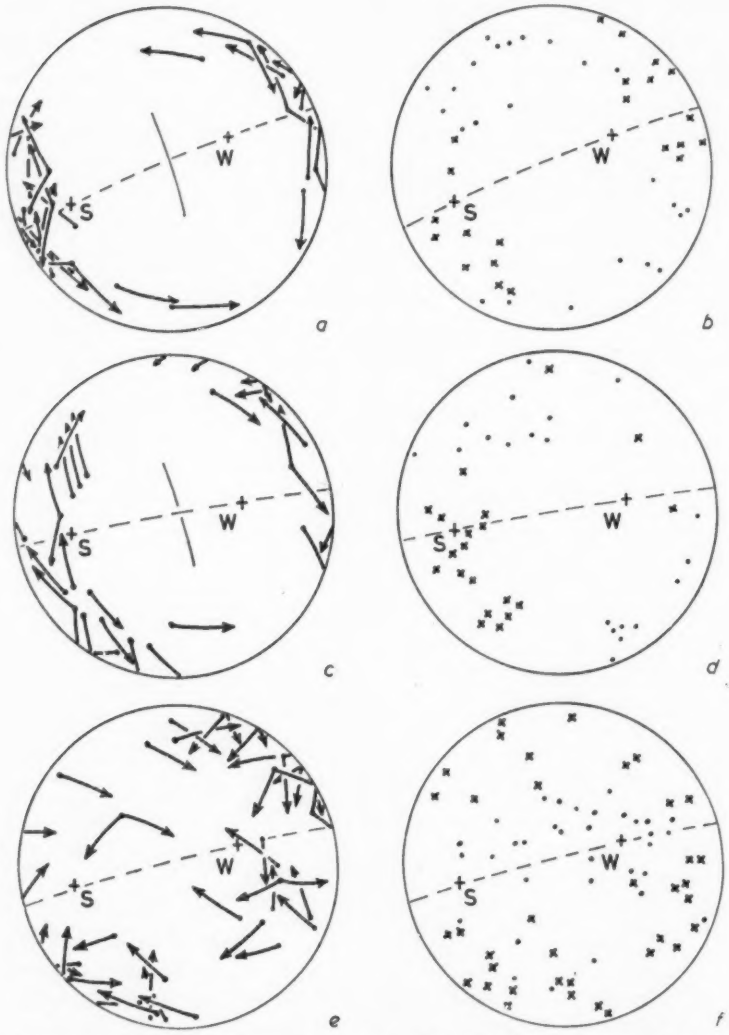
(*a*) Sp. 3. *c* axes (dots) and poles of {01$\bar{1}$2} twinned lamellae (arrow heads) of thirty-four twinned grains.

(*b*) Sp. 3. Axes of compression (dots) and tension (crosses) most favouring the observed twinning on {01$\bar{1}$2} in individual grains.

(*c*) Sp. 2. *c* axes (dots) and poles of {01$\bar{1}$2} twinned lamellae (arrow heads) of twelve twinned grains.

(*d*) Sp. 2. Axes of compression (dots) and tension (crosses) most favouring the observed twinning on {01$\bar{1}$2} in individual grains.

tension respectively were determined for each analysed specimen. These points are shown in Text-fig. 5 (*a*) (in which the data for three of the specimens have been rotated slightly about the *c* fabric axis in order to facilitate direct comparison). The correspondence is remarkable and demonstrates convincingly the homogeneity of the twinning throughout the exposure studied, and also the validity of data obtained from a sample of twenty twinned grains. It is obvious that even the twins found in this rock (which are very narrow compared with those in, for example, the Strathspey and Yule marbles) reflect a stress system operating in the *ac* plane.



TEXT-FIG. 4.—Strachur marble. Specimens 1, 2, and 4. Orientation as in Text-fig. 2.

(*a*) Sp. 1. *c* axes (dots) and poles of {01$\bar{1}$2} twinned lamellae (arrow heads) in twenty twinned grains.

(*b*) Sp. 1. Axes of compression (dots) and tension (crosses) most favouring the observed twinning on {01$\bar{1}$2} in individual grains.

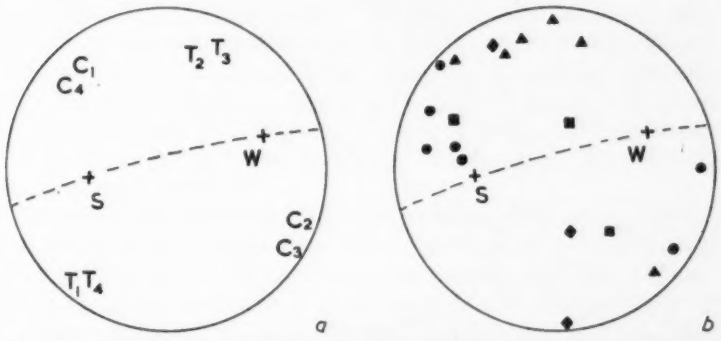
(*c*) Sp. 4. *c* axes (dots) and poles of {01$\bar{1}$2} twinned lamellae (arrow heads) in twenty twinned grains.

(*d*) Sp. 4. Axes of compression (dots) and tension (crosses) most favouring the observed twinning on {01$\bar{1}$2} in individual grains.

(*e*) Sp. 2. *c* axes (dots) and poles of {01$\bar{1}$2} twinned lamellae (arrow heads) of thirty-seven *very weakly* twinned grains.

(*f*) Sp. 2. Axes of compression (dots) and tension (crosses) most favouring the observed twinning on {01$\bar{1}$2} in the same thirty-seven grains.

The geometry of the calcite lattice is such that tension (applied subparallel to the *c* axis) can develop high resolved shear stress in the direction and sense appropriate for twinning on two or all three $\{01\bar{1}2\}$ planes simultaneously; but compression (applied normal to the *c* axis) favours twinning on only one $\{01\bar{1}2\}$ plane of a given grain. Consequently compression rather than tension is likely to have caused the development of twinning in those marbles in which grains with two



TEXT-FIG. 5.—Strachur marble. Specimens 1, 2, 3, and 4. Orientation as in Text-fig. 2. Specimens 1, 2, and 4 were rotated slightly about the *c* fabric axis to the orientation of Specimen 3. Hence foliation remains left and right; the top is, as before, the normal to the foliation in an upward direction.

(*a*) All specimens. Letters represent centres of fields of compression (C) and tension (T).

(*b*) All specimens. Bisectors of acute angles between glide lines e:r in nineteen grains with two sets of twinned lamellae each. Specimen 1, triangles; specimen 2, circles; specimen 3, squares; specimen 4, rhombs.

sets of twinned lamellae are rare; and this compression would be approximately parallel to the acute bisector [e:r] of the two sets of lamellae in such grains as do show double twinning (Turner, 1953, pp. 282–3). Nineteen grains with two sets of twinned lamellae were measured in the four specimens analysed. The acute bisectors of their glide lines are shown in Text-fig. 5 (*b*); the majority lie in the compression field of Text-fig. 5 (*a*).

In view of the very weak nature of the twinning in Specimen 2 attention was also paid to grains in which twinning was exceedingly faint even to the point of being doubtful. Data for the exceedingly faint twins observed in thirty-seven grains are recorded separately (cf. Text-figs. 3 (*c*) and 4 (*e*)). The difference between Text-figs. 3 (*d*) and 4 (*f*) suggests that many of the lamellae in question belong in fact to the "non-twinned" category which also includes the majority of the $\{01\bar{1}2\}$ lamellae observed in these marbles.

Orientation of Quartz and Mica

Apart from calcite, the only important minerals in the marble are quartz and mica. The micas show a well-marked orientation parallel to the foliation plane, with a faint girdle about *b*.

McIntyre and Turner (1953) found a random orientation of the *c* axes of quartz grains in the Tomintoul marble, although the calcites are well oriented in that rock. In the marble at Strachur quartz is

Text-fig. 6.—Strachur marble. Specimen 1. Orientation as in Text-fig. 2. *c* axes in 190 quartz grains from quartzose aggregates.

considerably more abundant than is the case in the Tomintoul marble, and the *c* axis was measured in 190 grains belonging to quartz aggregates in Specimen 1 (Text-fig. 6). There is apparently no preferred orientation.

Summary and Conclusions

The fabric of the marble throughout an outcrop 30 yards long is remarkably homogeneous. This applies not only to megascopic features such as foliation and lineation but also to preferred orientation of the calcite lattice (*c* and *a* axes) and to development of twinning. Directions of late stress deduced to account for twinning are likewise constant.

The fabric of the Loch Tay Limestone at Strachur strikingly resembles those of previously described, naturally deformed marbles. The *c* axes of calcite grains occupy a maximum near the pole of the foliation and spread into a distinct girdle normal to *b* and to the regional fold axis. Twinning can be explained by a simple system of stresses operating in the *ac* plane. Even in the quartzose lenticles there is apparently no orientation of the *c* axes of quartz. There are, however, several obvious differences between the Strachur marble and previously described marbles. Although the calcite grains are flattened parallel to the foliation, they are slightly elongate in *a* rather than in *b*. There is a weak

but distinct tendency for the *a* crystal axes of calcite to be oriented so that one of those axes is close to *b*. Twinning has occurred on $\{01\bar{1}2\}$ lamellae which are arranged to define two *s*-planes, one parallel and one normal to the foliation, apparently in response to a compression in *ac* directed at 45° to the plane of the foliation.

In the Cowal area the axis of folding on all observable scales, trends N. 55° E. with a very slight plunge to the south-west. There is a symmetry plane normal to the fold axis of the megascopic fabric. On the north-west limb of the Cowal " anticline ", in the Strachur region the sense of movement was towards the south-east as inferred from the shapes of folds, strain-slip cleavages and other megascopic evidence. Petrofabric analysis shows that the marbles all possess the same monoclinic symmetry. Both the general calcite fabric and the twinning confirm the direction of movement, but not the sense, derived from the megascopic structures.

The movements which controlled the formation of the *c* axis girdle for calcite during the main known phase of crystallization, apparently had the same symmetry as the later movements which produced the post-crystallization twinning on $\{01\bar{1}2\}$. Movements in the area seem to have been very constant in a direction normal to the regional fold axis. The persistence of the same *b* axis during the various deformations of the calcite contrasts strongly with the lack of orientation of the quartz. Even in the most quartzose schists so far examined, no preferred orientation of quartz has been detected and little or no undulose extinction has been observed. This suggests that quartz crystallized after the last movements. Although the mica crystals are parallel to the foliation in the marble and in the other rocks studied, they are not bent in strain-slip cleavages or in micro-folds, so that, presumably, they too finished crystallizing after the movements had ceased.

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The Granite Problem : Evidence from the Quartz and Feldspar of a Tertiary Granite

By O. F. TUTTLE and M. L. KEITH

ABSTRACT

The inversion temperatures of the quartz from twenty-five specimens of the Beinn an Dubhaich granite have been measured and found to correspond to the inversion temperatures of quartz from rhyolites previously studied. Optical and X-ray studies of the alkali and plagioclase feldspars indicate high temperature modifications. The Beinn an Dubhaich granite has the textural and compositional features of a granite together with mineralogical features normally associated with rhyolitic rocks. The results serve to emphasize that methods are now available which make it possible in some cases to determine whether a particular granite was formed by metamorphism of sediments or by crystallization of a magma. It is concluded that the older granites and those which crystallized at greater depths probably have undergone considerable rearrangement of their mineralogical and textural features subsequent to primary crystallization.

INTRODUCTION

THE continuing controversy regarding the origin of granite can be reduced in part to Bowen's purposely simplified statement (1948, p. 80): "The real question is, then: how much granite is magmatic and how much metamorphic?" The present study serves to emphasize that the decision as between a magmatic and a metamorphic origin of a particular granite mass should not be made without due consideration of the evidence available from the granite minerals. We are in fundamental disagreement with H. H. Read's view (1948, p. 2) that the granite problem is " . . . essentially one of field geology". Much of the granite controversy is a result of conflicting interpretations of field evidence and the present state of the problem is testimony to the inadequacy of field relations alone as a source of evidence for a final decision. We must now turn to other sources of evidence. The minerals of granites have stored up much information concerning their past history, and it is this storehouse of information which has been neglected and which now must be brought to bear on the problem. Any measurable variation in the minerals of granites is potentially a key to information regarding the processes of formation.

BASIS FOR USING QUARTZ AND FELDSPARS AS INDICATORS OF CONDITIONS OF CRYSTALLIZATION

Quartz.

Detailed study of the properties of quartz shows that it may yield information as to the conditions under which it crystallized. In a previous publication (Keith and Tuttle, 1952), the authors reported on a study of the inversion of some 250 quartz specimens from a wide

variety of geologic occurrences. The temperature of the high–low inversion of natural quartz was found to vary by as much as 38°, although over 95 per cent of the natural samples studied invert at temperatures within a range of 2·5°. Synthetic quartz prepared in the presence of ions which may be expected to substitute for silicon or occupy intratetrahedral positions in the quartz structure, shows differences in inversion temperature of as much as 160° C. *Inversion temperatures of synthetic quartz samples which grew in chemically similar environments are inversely related to the growth temperatures; there is considerable evidence that the same inverse relationship holds for most natural quartz.* It was concluded that the variations are due primarily to the presence in the quartz structure of small amounts of ions other than Si^{4+} and O^{2-}, and that the degree of incorporation of " foreign " ions is a function of temperature.

One of the interesting results of the earlier study concerns the quartz from a group of granites and rhyolites; the quartz from most of the granites inverts at a higher temperature than does the quartz from rhyolites. On a chart of the inversion-break on heating versus the inversion-break on cooling, the rhyolitic quartz and the granitic quartz show a statistical grouping into separate areas [1] (Text-fig. 2). It was therefore concluded that there is a significant difference between the environment of final crystallization of the quartz of rhyolites and that of most of the granites studied. The most probable explanation is that the quartz of many granites recrystallized during the low-temperature late stages of magmatic activity. Granites of metasomatic origin might be expected to exhibit similar differences from rhyolite, but only a few of the granites studied are types which would be considered as of replacement origin except by extreme proponents of granitization.

Feldspar.

Recent studies of synthetic and natural feldspars provide a basis for using feldspar as an indicator of relative temperature of crystallization. It has been shown, for example (Spencer, 1937; Tuttle, 1952*b*), that the optic axial angle of alkali feldspars will serve to distinguish high-temperature modifications from the low-temperature forms provided that the chemical composition is known. For this purpose the orthoclase content of an alkali feldspar can be determined by X-ray diffraction measurements. The relationship between composition and optic axial angle is shown in Text-fig. 4.

[1] There are a few exceptions among the granites included in the first study; four of them contain quartz similar to that of rhyolites. One quartz specimen, No. 50–30, was reported (Keith and Tuttle, 1952, p. 231) as rhyolite quartz with abnormally high inversion temperature; it has since been learned that sample 50–30 is from porphyritic granite.

High- and low-temperature sodic plagioclase feldspars can also be distinguished from one another by measurements of the optic axial angle, if the composition is known from analyses or from index of refraction measurements. The relationship between composition and optic axial angle is shown in Text-fig. 5.

Selection of a Granite for Detailed Study

If low-temperature recrystallization of primary mineral assemblages of granites is mainly responsible for the differences found between the quartz and feldspar of many granites and that of rhyolites, then it should be possible to find some granite masses, or at least offshoots or near-contact parts of granite bodies, which have cooled rapidly enough that the quartz and feldspar will not have recrystallized completely at low temperatures and will have retained some characteristics in accord with the conditions of primary crystallization. It is to be expected that the quartz and feldspar from a relatively young granite which has not been metamorphosed would be most likely to show characteristics resultant from the conditions of primary crystallization. Furthermore, a small granite mass whose roof is close to the present erosion level would seem to offer the best chance of obtaining samples of granite which has been quickly cooled and has undergone a minimum of recrystallization as a result of late-stage magmatic activity. The following is a preliminary report on the quartz and feldspar of the Beinn an Dubhaich granite which appears to satisfy the above requirements.

The Beinn an Dubhaich Granite

Occurrence.

The Beinn an Dubhaich granite is one of the Tertiary granites of the Island of Skye. The granite was described in some detail by Harker (1904); contact phases of the granite, as well as metamorphosed carbonate rocks adjacent to the contacts, were subsequently described by Tilley (1947, 1949, 1951).

The granite is a medium to fine-grained hornblende-biotite type with mosaic texture; local contact facies carry an alkaline pyroxene. The principal constituents are alkali feldspar, quartz, and plagioclase. Following is a modal analysis (volume per cent), the unweighted mean of 25 point-count analyses of stained thin sections [1] of samples from various parts of the granite mass.

Modal Analysis.

Quartz	29·7
Orthoclase	55·7
Plagioclase	10·8
Others	4·1

[1] Staining technique described by Keith (1939), modified by Chayes (1952).

The alkali feldspar is perthitic in part, but more commonly is optically homogeneous cryptoperthite. Near the contacts plagioclase is absent in several specimens, the granite there consisting essentially of alkali feldspar and quartz, plus from 1 to 8 per cent of dark minerals.

Sampling.

Twenty-five specimens of the Beinn an Dubhaich granite were collected; specimen locations in relation to the outline of the granite mass are shown in Text-fig. 1. Most of the specimens were collected near contacts; however, there is no evidence that the quartz of near-contact specimens is significantly different from quartz collected farther away from contacts. Part of each specimen was crushed and sieved and the quartz and feldspar were separated for study.

Investigation of Quartz.

The inversion temperature of each sample of separated quartz was determined by a differential thermal method, the details of which are given in a previous publication (Keith and Tuttle, 1952). The differential thermal method does not give the equilibrium temperature of the quartz inversion; that is, the temperature at which the high and low forms coexist in equilibrium. However, by keeping the sample size, grain size, and heating rate constant within narrow limits and by using reference materials [1] heated under identical conditions at the same time, it is possible to choose points on the thermal curves which yield inversion temperatures reproducible to $\pm 0{\cdot}1°$ C. Previous experience has shown that a point at the intersection of the base-line with a line drawn along the first straight portion of the differential curve due to inversion is easily located and reproducible, and the chart can be scaled to give a temperature close to the equilibrium temperature of inversion. Temperatures of points located in the above manner are used throughout the present discussion, and are referred to as inversion-break temperatures or inversion temperatures.

Quartz from the Beinn an Dubhaich granite inverts at temperatures from 572·3° to 572·7° on heating and 573·1° to 572·6° on cooling. Two samples, F2–166 and F2–192, exhibit double inversions indicative of the presence of two different types of quartz; F2–192 has only a small amount [2] of quartz with a lower temperature inversion. The

[1] Reference materials used:—

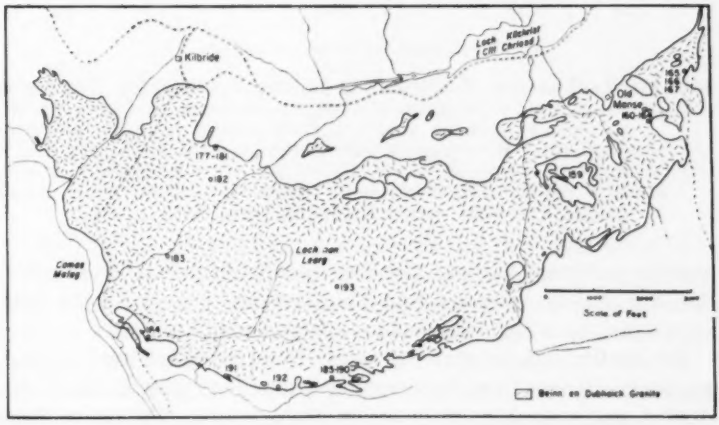
Rose quartz, sample 52–4	Inversion-break on heating 570·5°
	Inversion-break on cooling 570·3°
Ivigtut cryolite . .	Inversion-break on heating 563·0°
	Inversion-break on cooling 562·7°
Purified K_2SO_4 . .	Inversion-break on heating 583·5°
	Inversion-break on cooling 584·9°

[2] Amounts estimated approximately from relative peak heights on the differential thermal records.

TABLE 1.—INVERSION-BREAK TEMPERATURES OF QUARTZ FROM THE BEINN AN DUBHAICH GRANITE

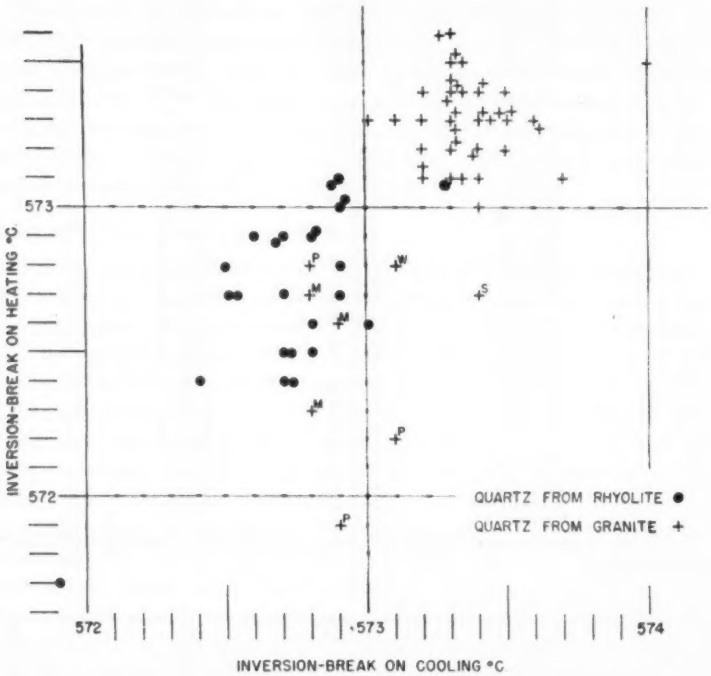
Sample No.	*Inversion on Heating.*	*Inversion on Cooling.*
F2–159	572·6	572·6
F2–160	572·5	572·8
F2–161	572·5	572·7
F2–162	572·6	572·7
F2–163	572·5	572·7
F2–164	572·4	572·6
F2–165	572·6	573·0
F2–166*	— 572·3	572·9 —
F2–167	572·4	572·6
F2–177	572·7	572·8
F2–178	572·6	572·9
F2–179	572·5	572·8
F2–180	572·6	573·0
F2–181	572·7	572·8
F2–182	572·6	572·9
F2–183	572·6	572·8
F2–184	572·5	572·6
F2–185	572·5	573·0
F2–186	572·6	573·1
F2–187	572·6	573·0
F2–188	572·6	572·7
F2–189	572·7	572·9
F2–191	572·6	572·7
F2–192*	572·4 571·7	572·6 —
F2–193]	572·6	572·7
F2–229	572.5	572.8

* Double inversion—previous experience indicates that two types of quartz are present.



TEXT-FIG. 1.—Map of the Beinn an Dubhaich granite (after C. E. Tilley, 1951, Plate xxiv), showing location of specimens studied.

results of inversion temperature measurements are listed in Table 1 and illustrated in Text-fig. 3. Comparison of Text-figs. 2 and 3 shows that quartz from the Beinn an Dubhaich granite falls in a chart area occupied primarily by quartz from rhyolites. Not one of the samples has an inversion falling in the principal chart area of quartz from



TEXT-FIG. 2.—Inversion of quartz from granites and rhyolites. The higher temperature of inversion of most granitic quartz studied is believed to indicate that the quartz recrystallized at relatively low temperatures. M = granites from three localities in Maine: North Sullivan, Jonesport, and Wallace Cove. P = Pike's Peak granite. W = granite from Westwood, Mass. S = White Silver Plume granite, Colorado. (After Keith and Tuttle, 1952, p. 231.)

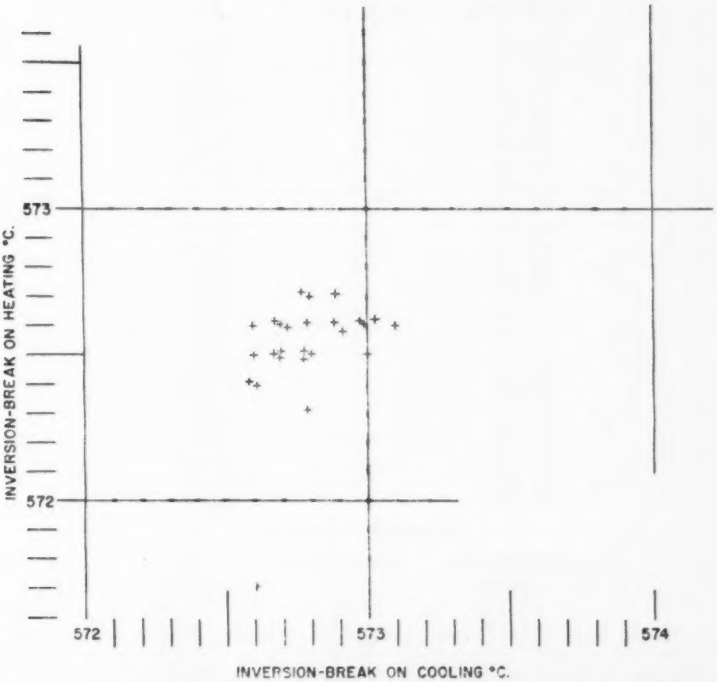
granites previously studied. Granites included in the earlier investigation are mainly Paleozoic and Pre-Cambrian granites, some from areas which have been subjected to regional metamorphism.

The results indicate that the quartz from the Beinn an Dubhaich granite is different from the quartz of most of the granites previously studied, and resembles, in inversion characteristics, the quartz from rhyolites. It can be inferred that the quartz from this particular Skye granite has undergone little recrystallization and therefore has retained

inversion characteristics dependent upon the conditions of primary crystallization.

Measurements on Feldspars.

The above results on quartz led to an examination of the feldspars with the object of obtaining further evidence regarding the conditions of crystallization of the Beinn an Dubhaich granite. A brief study of



TEXT-FIG. 3.—Inversion-break temperatures of quartz from the Beinn an Dubhaich granite. Compare with Text-fig. 2 which illustrates inversion of quartz from granites and rhyolites previously studied.

the alkali and plagioclase feldspars indicates that they have properties which resemble closely those of the feldspars of rhyolites.

The alkali feldspars of twenty-three specimens of the granite were separated by heavy liquids and the optic axial angles were measured on the universal stage, using the interference figure method; measurements on a single grain are reproducible to $\pm 1°$. The composition was determined in each case by X-ray diffraction, using the $(\bar{2}01)$ spacing according to the method described by Bowen and Tuttle (1950). It should be noted that the X-ray method, as applied to the

present problem, gives only the "orthoclase-content"; albite and anorthite proportions are not determinable by means of measurements of the (201) spacing. The results of the determinations of composition and optic angle are listed in Table 2 and are plotted in Text-

TABLE 2.—OPTIC AXIAL ANGLES OF FELDSPARS

Alkali Feldspars.

Specimen No.	*Or Content by X-ray**	$2V_a$.
F2–159	71	44–66
F2–160	60	52–67
F2–161	76	52–60
F2–162	62	52–73
F2–163	61	53–62
F2–164	61	38–66
F2–166	66	59–74
F2–178	66	51–61
F2–179	64	54–63
F2–180	66	52–64
F2–181	58	47–60
F2–182	65	46–59
F2–183	59	52–64
F2–184	63	48–60
F2–185	61	43–69
F2–186	61	53–67
F2–187	61	56–68
F2–188	59	49–63
F2–189	62	53–63
F2–191	60	54–63
F2–192	57	58–68
F2–193	70	46–62
F2–229	55	44–58

Plagioclase Feldspars.

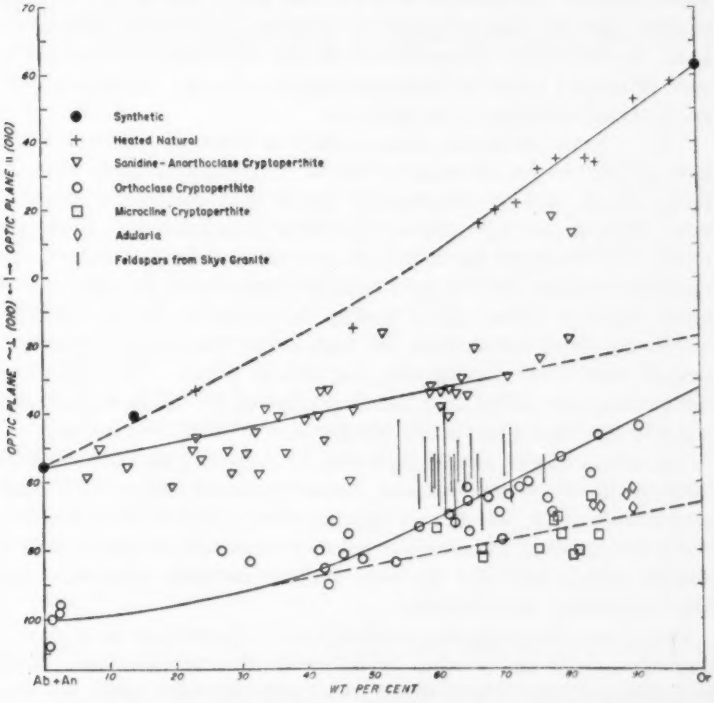
Specimen No.	*Composition.*	$2V$.
F2–178	N.D.†	75–80
F2–183	N.D.	76–79
F2–187	N.D.	78–79
F2–193	N.D.	76–81
F2–229‡	An_{19}	68–70

* Orthoclase content determined on samples heated thirty-seven days at 1,050° C.; 2V measured on unheated grains.
† N.D. = not determined.
‡ Cambridge University No. 28520.

fig. 4. Dr. N. L. Bowen collaborated on the optical measurements on alkali feldspar.

The optic axial angles of the alkali feldspars examined are intermediate between those of alkali feldspars from rhyolite and those of low-temperature cryptoperthites of most granites and pegmatites (Text-fig. 4). All of the measured alkali feldspars show a considerable range in 2V; it is noteworthy that some grains have optic angles very close to those of sanidine of corresponding composition. The range in 2V is attributed to partial transformation from sanidine to orthoclase

cryptoperthite; comparative index of refraction measurements on grains having 2V = 45° and 2V = 58° indicate that little, if any, of the variation can be attributed to compositional differences. Single-crystal X-ray studies of the alkali feldspars support the thesis that the



TEXT-FIG. 4.—Graph showing the relation between optic axial angles and composition of alkali feldspars. Vertical lines illustrate the range in $2V_a$ of twenty-three alkali feldspars from the Beinn an Dubhaich granite. (After Tuttle, 1952*b*.)

variation in 2V is a result of partial transformation to low temperature forms.

The authors are indebted to Drs. W. S. MacKenzie and W. H. Taylor of Cambridge University for single crystal studies of one of the feldspars. In regard to the use of single crystal X-ray diffraction studies and the results on a specimen from the Beinn an Dubhaich granite, MacKenzie writes as follows (personal communication):—

" Single crystal studies of cryptoperthites by Chao and Taylor (1940) and by Laves (1952) have shown that the soda phase may be either low albite twinned according to the Albite Law, or high albite twinned according to the Pericline Law. A single crystal, ' b '-axis oscillation

photograph of low-temperature *orthoclase cryptoperthite* of composition about $Or_{60}Ab_{40}$ shows, in addition to the monoclinic potash phase, a set of spots corresponding to low albite twinned according to the Albite Law. A similar photograph of a *sanidine cryptoperthite* of the same chemical composition shows a soda phase represented by a set of spots corresponding to high albite twinned according to the Pericline Law. It thus seems reasonable to use this difference in the exsolved soda phase as a means of distinguishing between an orthoclase cryptoperthite and a sanidine cryptoperthite.

"A 'b'-axis oscillation photograph was taken of a crystal of the Skye feldspar [1] with the centre of the 15° oscillation arc parallel to the (001) planes, and the photograph shows both low albite in albite twin relations and high albite in pericline twin relations. From the relative intensities of the reflections representing the two phases, this material would appear to have approximately equal amounts of low albite and high albite. After heating the crystal at 700° C. for three hours, the spots representing the high albite had almost completely merged with those representing the potash phase. The reflections representing low albite were largely unaffected by this heat treatment and still persisted after further heating at 850° for fifteen hours."

The above results can be explained by assuming that the perthitic intergrowth of potash feldspar, low-temperature albite, and high-temperature albite, was once a homogeneous alkali feldspar, *sanidine*, which has unmixed on cooling to nearly pure potash feldspar and soda feldspar phases and that the soda feldspar partially inverted to the low-temperature modification.

High- and low-temperature plagioclase feldspars can also be distinguished from one another by determinations of optic axial angle and composition. Optic angle measurements were made on five specimens of plagioclase from the Beinn an Dubhaich granite and the results are set down in Table 2. The composition of one plagioclase, that from Specimen F2–229, was determined by index of refraction measurements; the result is plotted on Text-fig. 5, which is modified from Tuttle and Bowen (1950). The optic axial angle, 68° to 70°, falls close to the curve for high-temperature plagioclase and is too low for any known low-temperature plagioclase.

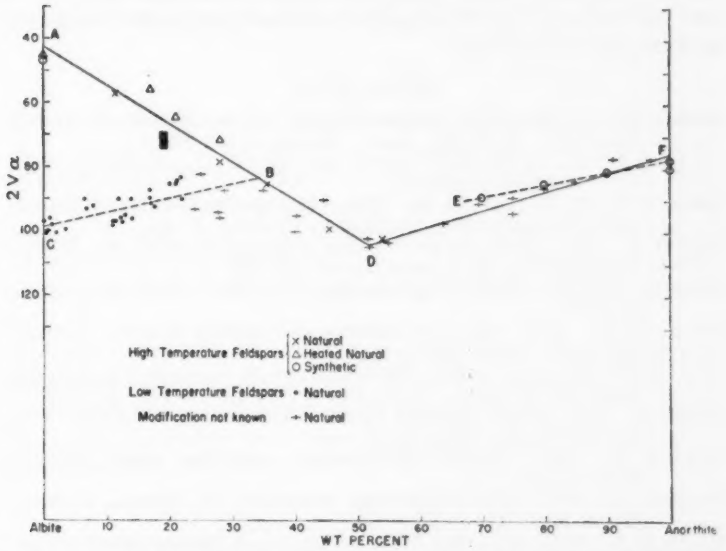
Discussion

The Beinn an Dubhaich granite has the textural and compositional features of a granite together with mineralogical features normally found in rhyolites, and therefore is considered to supply what may be termed a missing link between granites and rhyolites. Studies of the

[1] Specimen F2–229 (Cambridge University No. 28520), $2V = 53°$.

high–low inversion indicate that the quartz probably crystallized in a temperature range comparable to the temperature of crystallization of rhyolite quartz. Optical and X-ray studies of the feldspars indicate that they are partially changed from high temperature types to intermediate or transitional varieties.

Detailed mineralogical features, as well as the field relations, support



TEXT-FIG. 5.—Optic axial angles of high- and low-temperature plagioclase feldspars. The solid bar at An_{19} ($2V = 68°$ to $73°$) represents the optic axial angle and composition of plagioclase feldspar in specimen F2–229 from the Beinn an Dubhaich granite. (After Tuttle and Bowen, 1950.)

the thesis that the Beinn an Dubhaich granite represents a crystallized granitic magma which has been only partly recrystallized subsequent to the orthomagmatic stage. Had this granite been emplaced at a greater depth where cooling would have been of longer duration and where higher pressure would tend to prevent escape of volatile constituents, it is probable that the feldspars and quartz would have undergone further and more profound changes and may well have taken on the features of the minerals of more common " two-feldspar " granite containing microcline, low albite, and low-temperature quartz.

The Skye granite provides a clue to the thermal behaviour of feldspars and quartz and is worthy of further study, both chemically and mineralogically. A cursory examination of the minerals of other young unmetamorphosed granites indicates that the mineralogical features

of the Beinn an Dubhaich granite are found in other granites which have cooled rapidly enough to prevent complete recrystallization. There is no question that some granites and granite gneisses are formed by metasomatic processes; it is likely, however, that detailed study of the mineralogy, as well as the field relations of different granites, will show that many of the textural and structural features of granites that are attributed by some investigators to metasomatism and granitization may well be imprints of late-stage recrystallization on normal magmatic granites and their contacts.

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Relations of Torridonian to Durness Limestone in the Broadford–Strollamus district of Skye

By E. B. Bailey

Abstract

Evidence strongly suggests that the Durness Limestone in Skye is a great thrust-slice between Torridonian above, at Broadford, and Torridonian below, at Strollamus and Scalpay.

Introduction

THE relationship of the Torridonian near Broadford to the Torridonian of Scalpay has been recognized for fifty years as an outstanding puzzle of North-West Highland geology. The field evidence is admirably represented in the Geological Survey's 1910 one-inch Sheet 71, based on Clough's six-inch mapping at Broadford and Harker's at Strollamus. Additional detail in regard to the latter locality is furnished in a 10½ inches to the mile map by B. C. King (1953).

I spent a week in 1953 on the ground, during which I enjoyed invaluable help from E. H. Francis. I wish also to acknowledge very welcome financial assistance from the Carnegie Trust; and to thank the Geological Survey most heartily for permission to consult their manuscript field maps.

Pre-Mesodoic Rocks

Torridonian (*Pre-Cambrian*).—The island of Scalpay is fashioned out of Torridonian. Harker has divided the succession in descending order as follows (1910, p. 63):—

Coarse felspathic grits, 4,750 feet seen
Fine felspathic flaggy sandstones, more quartzose below, 1,300 feet seen

Torridonian has also been identified in neighbouring parts of Skye—at Creag Strollamus (t) and again south of Broadford (t^k, Text-fig. 1). At Creag Strollamus the prevalent rocks are some 1,500 feet of thinly-bedded fine-grained felspathic sandstones, only occasionally gritty. Harker remarks that they appear to correspond with the lower group of Scalpay, and such a correlation may well be true. If so we must interpret the sandstones at Strollamus as thrust over the grits which, in Scalpay, overlie them; but this is a matter which cannot be discussed here. The Strollamus sandstones strike N.E. and are either vertical or steeply inclined S.E. They are often much shattered. The best exposures lie in the half-mile south of the summit of the Creag.

The Torridonian south of Broadford has been convincingly claimed by Clough as Middle Torridonian, that is Applecross Grits (1910, p. 60).

Quartzite (*Incerti Sedis*).—The Strollamus Torridonian is locally associated with very minor outcrops of quartzite, which may quite possibly be relics of the Cambrian Durness Quartzite. They are not separated in our text-figures from the Torridonian.

Durness Limestone (*Cambro-Ordovician*).—Geikie accompanied by Cadell long ago demonstrated (1888) that a great thickness of Durness Limestone, occasionally fossiliferous, occupies an extensive region of Skye.

Mesozoic and Tertiary Rocks

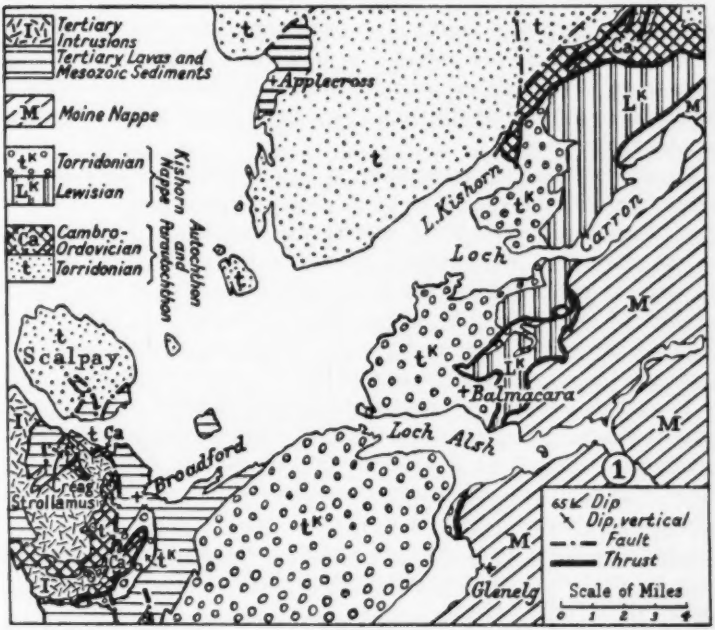
Mesozoic rocks of the district are entirely sedimentary, with Trias (thin), Jurassic (thick), and Upper Cretaceous (thin). Tertiary rocks include a big thickness of basalt lavas, and a number of intrusions, mainly dolerite and granophyre.

Structural Relations of Torridonian to Durness Limestone

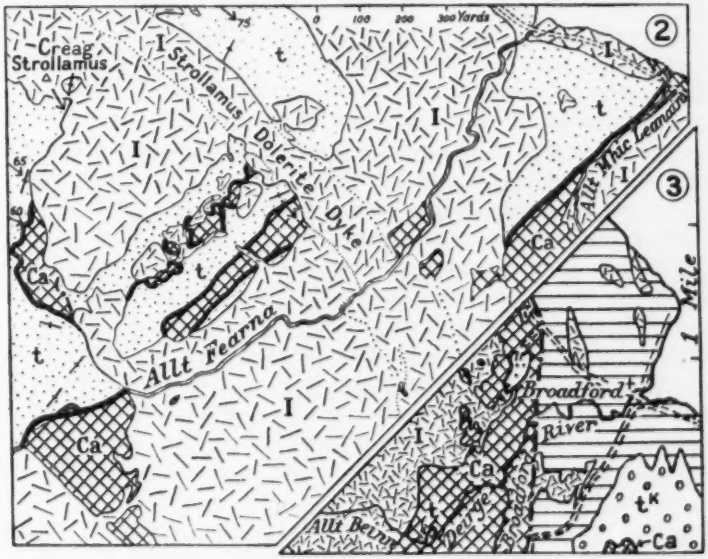
Broadford is situated 6 miles N.W. of the outcrop of the Early Palaeozoic Moine Thrust at the base of the Moine Nappe (Text-fig. 1). The intervening country is composed of Torridonian carrying a synclinally disposed cover of Mesozoics. Immediately south of Broadford the Torridonian rises anticlinally through the Mesozoics; it is much thinner than further east, and a mile south of the village it has been eroded to expose a broad axial outcrop of Durness Limestone. The superposition of Torridonian on Durness Limestone is self-evident, and is attributed to the Kishorn Thrust (also Early Palaeozoic). All this has been well known since the publication of a brief account by Clough (Geikie, 1896, p. 21); and perhaps even longer.

On the west side of the Broadford anticline, the Durness Limestone passes under Torridonian, which in turn passes under Mesozoic; and this latter, a mile west of the village, is cut off by a N.–S. fault bringing Durness Limestone once more to the surface (Text-fig. 3). So far all is clear; but west of the N.–S. fault I think that mistakes have been made.

At about three-quarters of a mile beyond the N.–S. fault there is a small outcrop of Torridonian in Allt Beinn Deirge of Text-fig. 3. It occurs in the heart of Durness Limestone country; and, as there is no room for anything like a full representation of Durness Quartzite at the contact of Torridonian with limestone, it must be bounded by a thrust. Clough (1907, fig. 61, and p. 580) treated it as a klippe, riding on the Kishorn Thrust. Possibly he never saw the exposure, and merely



TEXT-FIG. 1.



TEXT-FIG. 2. TEXT-FIG. 3.

TEXT-FIG. 1–3. Maps of Broadford & Strollamus. Mainly after Geol. Surv.

reproduced notes from Harker who had mapped the area (*cf.* Harker, 1910, p. 80). I have not visited it, but Harker's field map shows that there is no sufficiently close approach of Torridonian and limestone exposures to indicate whether the Torridonian lies on top of its neighbour, or *vice versa*.

Fortunately a similar occurrence, 1½ miles further N.E. (a mile due west of Broadford Bridge, Text-fig. 3) gives a better chance of observation. Here Harker says that " several small outliers of Torridon rest on the limestone " (he indicates four separate thrust-limited patches on the one-inch map). There is no difficulty to-day in finding the locality, for it is crossed by a new road that branches at right angles from the Broadford–Portree highway. Moreover, slightly improved exposures make it almost certain that there is only one irregular patch of Torridonian instead of four. The Torridonian tends to be covered beneath a smooth grassy surface, while the adjacent limestone (marble), largely bare rock, rises a few feet immediately outside, thus furnishing a low upstanding rim, admittedly discontinuous. I think it practically demonstrated that we have in this case a window which in the past has been mistaken for a group of klippen; and that we are dealing with a thrust that has brought younger beds (Durness Limestone) across older (Torridonian).

Further N.W., at the streams Allt Mhic Leanain and Allt Fearna (Text-fig. 2), we pass in complicated fashion from Durness Limestone country on to Torridonian country. The contact runs S.W. from the coastal high road for 500 yards; and for half of this distance it is followed by the lower course of Allt Mhic Leanain. Harker has mapped this junction as due to an outcrop of the Kishorn Thrust, remarking that the lower part of the stream is a good place to observe the relation of the Torridonian " to the limestone below "; but the contact is steep, and King regards it as mostly determined by a series of small faults cutting out the actual thrust (1953, p. 368, and D of fig. 1).

The next good exposures of associated Torridonian and Durness Limestone lie on the other side of what I call the Strollamus dolerite dyke. In these limestone is found 500 yards further N.W. than along the Allt Mhic Leanain line. Starting from the dyke there are two rows of limestone outcrops, both running S.W., parallel, that is, with the Allt Mhic Leanain line, and also with the prevalent strike of neighbouring Torridonian. The more north-westerly row measures 400 yards in length and includes five separate patches of exposed limestone. Of these, the largest is about 100 yards long and 70 broad; while the smallest, practically against the dyke, is minute. Exposures are not good enough to establish geometrical relations, beyond the obvious fact that irregular patches of limestone, accompanied by dolerite and granophyre, are strung out in line in a Torridonian setting. Both

Harker and King interpret these patches as marking little windows opened down through the Kishorn Thrust.

South-east of the patchwork belt just described, and separated from it by a band of Torridonian some 70 yards wide, lies a parallel but continuous limestone outcrop, more than 400 yards long and 30 to 100 yards wide. It starts against the Strollamus dolerite dyke. The Torridonian to the N.W. is well enough exposed. That to the S.E. was first noted by King, and very little of it is seen before granophyre is reached. Harker has mapped the comparatively well-exposed N.W. boundary as Kishorn Thrust. King on his coloured plate treats the whole strip as a window exposure surrounded by Kishorn Thrust. He seems, however, to have realized that field appearances suggest that the N.W. boundary is a shear-plane steeply inclined S.E., the usual direction for the bedding of the Torridonian. He has accordingly proposed in his text that on this side the thrust is really replaced by a small fault, as in Allt Mhic Leanain (1953, p. 368, and C in fig. 1).

Further west, still in Text-fig. 2, limestone reappears in two localities. One outcrop runs roughly N. and S. for about 300 yards, and has conspicuous quartzite along part of its western flank. The other is bounded to the north by Allt Fearna, and runs W.S.W. It starts a little S. of the line of the continuous band that lies S.E. of the patchwork. Harker does not reproduce the N.–S. outcrop on the Survey one-inch map; but King surrounds it with the Kishorn Thrust. Both treat the Allt Fearna contact as faulted, rather than merely thrust, against Torridonian to the north.

Conclusions

Everyone agrees that all contacts between Torridonian and Durness Limestone seen in the Strollamus district are mechanical. For my own part I do not feel able in this extremely difficult country to distinguish between steep faults and steep thrusts on the basis of available evidence; and readers must bear this in mind in looking at Text-fig. 2, where all Torridonian-limestone junctions are shown as thrusts. King has accepted from Harker that there is only one thrust concerned, the Kishorn Thrust, carrying Torridonian over limestone. He has further assumed that this thrust everywhere lies at a gentle angle, without any relation to the bedding of either Torridonian or limestone. To meet difficulties in actual exposures, he has interpreted certain obviously steep contacts as due to small post-thrust faults, with throws " probably never more than 50 feet ". Building on this composite basis, he has contoured the Kishorn Thrust (1953, pp. 366–9, and fig. 1). The result can only be regarded as a statement of hypotheses, not of evidence.

In my opinion anyone familiar with thrust-tectonics would interpret

the contact of Torridonian and limestone at Strollamus as almost certainly a thrust zone, including in some cases thrust-bounded slices of limestone, and, in the patchwork belt, even separated blocks. Moreover the individual thrusts of the zone seem generally to incline steeply S.E., parallel, that is, with the usual attitude of the bedding of the Strollamus Torridonian. This suggests that the thrusting has brought the Durness Limestone over underlying Torridonian, repeating the relation seen 1 mile W. of Broadford—not *vice versa* as previously supposed. I accept such local appearances as trustworthy, essentially because they enable me to attach the Strollamus Torridonian, somewhat loosely perhaps, to the generally accepted autochthonous Torridonian of Scalpay. I say "generally accepted" because Harker, who was, like myself, much impressed by the Strollamus-Scalpay association of Torridonian outcrops, saw in it an argument for interpreting the Scalpay Torridonian as part of the Kishorn Nappe; but this is a conception that Peach and others always thought highly improbable.

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The Clinopyroxene-hornblende Equilibrium in Thermal Metamorphism: Some Data from Carlingford, Eire

By W. T. Harry

Abstract

In a Tertiary ring complex at Carlingford, Eire, a large mass of eucrite is cut by porphyritic cone-sheets. A major granophyre intrusion later than the cone-sheets alters the clinopyroxene of the sheets to hornblende whilst the clinopyroxene of the adjacent eucrite remains unaltered. By elimination of several possibilities it is shown that the different behaviour of the two pyroxenes reflects their thermal stabilities.

It is argued that the two pyroxenes represent a pyroxene trend of crystallization and that thermal metamorphism attacked them in the reverse order of their magmatic crystallization. Importance is attached to extensive replacement of Ca'' by Fe'' in the cone-sheet pyroxene as a factor of instability.

Field Observations

On the western slopes of Carlingford Mountain eucrite lies in contact with a large mass of granophyre, younger than the eucrite and occupying the centre of the complex. The eucrite is cut by numerous basic cone-sheets dipping in towards the centre of the complex at about 45°. Richey (1932, p. 107) distinguishes two sets of cone-sheets, one earlier than the granophyre, the other later. The earlier set is characterized by abundant feldspar phenocrysts which, on weathered surfaces, lend a pock-marked appearance to the rock due to their differential weathering. The other set, which cuts the granophyre, is non-porphyritic dolerite similar to the Talaidh type characteristic of the late Basic Cone-sheets of Mull.

On the eastern slopes of Carlingford Mountain the porphyritic cone-sheets are numerous and strike approximately north-west. Richey (1932, p. 107) remarks that on the south-east side of Carlingford Mountain these cone-sheets cutting the eucrite and adjacent to the granophyre are in an altered condition.

The writer made several traverses from north-east to south-west across Carlingford Mountain with the object of studying the alteration of the porphyritic cone-sheets as the margin of the granophyre was approached. About half or three-quarters of a mile from the granophyre the dark groundmass of the porphyritic cone-sheets assumes a greenish tint due to the replacement of pyroxene by hornblende. This replacement is most intense around the summit of Slieve Foye. The eucrite, however, is unaltered right up to the granophyre contact.

Petrography

Eucrite.—The component minerals of this rock are bytownite, diallage, and olivine (Richey, 1932, p. 104). The plagioclase, which

composes most of the rock, is fresh and in large subhedral crystals, with broad albite twin lamellae. The latter sometimes are slightly displaced along microscopic fractures. Clinopyroxene, moulded on to the feldspar, is pale brown almost colourless in thin section and optically positive. Fifteen specimens of eucrite, chiefly from the margins of altered cone-sheets, were collected and sliced. In thin-section their pyroxene was unaltered. Some slices were traversed by lines of granulation along which pyroxene plates were broken down into aggregates of small crystals without trace of alteration to hornblende. It is worth recording that although about three miles west of Carlingford Mountain, and therefore beyond the area here dealt with, the eucrite of the Carlingford complex forming Black Mountain is strongly shattered and lies near the granophyre forming the centre of the complex, yet the broken pyroxenes show no signs of replacement by hornblende.

A specimen collected 500 yards south-west of Slieve Foye summit showed eucrite in contact with granophyre. Where the eucrite pyroxene was cut by granophyre a thin ·01 mm. thick border of green hornblende (perhaps an overgrowth) separated the pyroxene from the granophyre. Otherwise the eucrite pyroxene showed no evidence of metamorphic action.

A large specimen of fresh eucrite was taken from an exposure near an altered porphyritic cone-sheet 2,000 feet due geographical north from Slieve Foye summit. The clinopyroxene was separated from this and chemically analysed with results given in Table I (column 2). The same table gives certain optical data. Refractive indices were determined by the immersion method with estimated error $\pm$ ·003. Measurements of 2 V in sodium light on the Universal Stage were obtained by rotation from one optic axis to a bisectrix and gave a wide range of values. Commenting on this method of measurement Hess (1949, p. 629) remarks that errors of 5 degrees are fairly common and that the accuracy is apparently less than would be supposed from the literature.

An interesting feature of the analysed pyroxene is the deficient z group. Titanium is required to raise the value of this group up towards 2. It seems necessary therefore to assume the replacement of silicon by titanium in this pyroxene. Such replacements have been proposed by Dixon and Kennedy (1933), and recently Muir (1951). Apart from this feature the eucrite pyroxene shows many similarities with the diallagic pyroxene from the eucrite of Barnavave Mountain, a mile or so south of Carlingford, which Nockolds compares with the pyroxene of the Skye gabbro (1938, p. 477).

Porphyritic cone-sheets.—These rocks are olivine-poor dolerites. The less altered specimens can be seen to be sub-ophitic in texture, the plagioclase laths frequently wedging out into the pyroxene plates. The

pyroxene is a pale brown optically positive monoclinic variety with no obvious pleochroism and forming crystals up to about 1 mm. wide. In porphyritic cone-sheets from the immediate neighbourhood of Slieve Foye summit the pyroxene is completely replaced by hornblende. In specimens collected from numerous porphyritic cone-sheets between

TABLE 1.—ANALYSES AND OPTICAL PROPERTIES OF CLINOPYROXENES

	1. *Metal atoms to 6 oxygens.*				2. *Metal atoms to 6 oxygens.*			A.
SiO_2	48·43	1·856	0·144	2·000	50·37	1·848		50·63
Al_2O_3	4·38	0·197	0·053		2·84	0·125	1·990	3·28
TiO_2	2·24	0·064			0·62	0·017		0·63
Fe_2O_3	2·06	0·059		1·314	0·90	0·025		1·53
FeO	13·32	0·425			7·74	0·241	1·174	8·92
MnO	0·23	0·007			0·24	0·008		0·10
MgO	12·28	0·706			16·07	0·900		14·80
CaO	14·54	0·597		0·663	20·43	0·818		19·34
Na_2O	0·73	0·054			0·27	0·019	0·839	0·16*
K_2O	0·26	0·012			0·04	0·002		—
H_2O −	0·29				0·15			0·88
H_2O +	1·08				0·43			
								100·27
CO_2	nil				nil			
P_2O_5	traces				traces			
	99·84				100·10			* total alkali as Na_2O

1. Clinopyroxene from porphyritic cone-sheet, Carlingford, anal. Herdsman (see text for location).
2. Diallagic pyroxene from eucrite, Carlingford, anal. Herdsman (see text for location).
A. Diallagic pyroxene from normal eucrite, Barnavave (Nockolds, op cit.).

	1.	2.
α	1·692	1·683
γ	1·718	1·708
$\gamma-\alpha$	0·026	0·025
2V (+)	range 49–51°	51–60°
	mean 50°	55°
Atomic %	Ca 33	41
	Mg 39	45
	Fe 27	14

Slieve Foye and Carlingford Lough this replacement gradually decreases to zero on proceeding towards the Lough, away from the granophyre. The replacing amphibole forms thin fibres of moderate birefringence with pleochroism pale brown to green. The fibres are arranged parallel to each other in sheaves associated with chlorite and sometimes a little carbonate. Usually only one such sheaf replaces an individual pyroxene crystal.

In the most intensely altered porphyritic cone-sheets lying in contact with granophyre 500 yards south-west of Slieve Foye summit the dark mineral phase has been partly recrystallized to a pyroxene dissimilar to that of the unaltered cone-sheets. Thin-sections cut across the contacts show the dolerite to be granoblastic with a very pale coloured clear pyroxene associated with patches of green hornblende after pyroxene.

Basic plagioclase occurs in two generations. Large phenocrysts up to ½ inch long but usually about half that size can be plentiful. There is a tendency for the phenocrysts to be most abundant in specimens nearest the centre of the complex. Both generations of plagioclase show little trace of alteration but frequently they are traversed by microscopic fractures which, in altered cone-sheets, are often filled with chlorite and amphibole. A marked feature is the comparative absence of albitization, for such a British Tertiary rock.

In some specimens there occur scattered pseudomorphs after what may have been olivine or hypersthene and composed of chlorite, carbonate, amphibole, and iron ore. A common but not ubiquitous accessory is iron ore in grains.

Material was collected from a porphyritic cone-sheet near the Golden River, 1,200 yards and bearing 72° east of (geographical) north from Slieve Foye summit. In this rock replacement of clinopyroxene by hornblende had commenced but was not extensive, and the clinopyroxene was separated and chemically analysed (Table I, column 1).

Discussion

Replacement of pyroxene by hornblende in the porphyritic cone-sheets cannot be satisfactorily explained by autometamorphism. That explanation would be most unlikely from comparison with similar basic intrusions in other British Tertiary centres and moreover the porphyritic cone-sheets of Carlingford notably lack such common autometasomatic phenomena as albitization. On the other hand the replacement is spatially related to the large granophyre intrusion west of Carlingford Mountain, in a manner leaving little doubt that replacement was due to thermal metamorphism by the granophyre. Conversion of augite to hornblende is the most constant result of thermal metamorphism of gabbro, dolerite, or basalt (Harker, 1939, p. 107).

Since the granophyre cuts both eucrite and porphyritic cone-sheets it must be explained why the pyroxene of the former remained stable whilst that of the latter was uralitized. To this end possible significant differences between the parent rocks must first be sought. Both are of similar mineral composition except for the presence of fresh olivine in the eucrite. Apart from iron ore the cone-sheets contain no mineral phase additional to these in the eucrite which might have promoted

reaction. But the presence of iron ore was apparently of no importance for the reaction because some cone-sheets with abundant hornblende contain no iron ore, whilst certain eucrite slices show unaltered pyroxene in contact with iron ore derived from olivine. The bulk chemical composition of the reacting system also seems to have played no part in the replacement because the chemical compositions of eucrite and cone-sheets are obviously similar.

The two rocks differ in texture, however. Generally the cone-sheet pyroxene forms smaller crystals than the eucrite pyroxene with the result that the cone-sheet pyroxene presents a greater surface area relative to volume than the eucrite pyroxene. But this would only explain a lesser degree of alteration, not its absence, in the eucrite pyroxene.

Careful attention must be given to the possibility that the pyroxene-hornblende reaction under discussion was promoted by hot fluids emanating from the granophyre and that the eucrite pyroxene was not affected because the eucrite was less permeable to those fluids than the cone-sheets. There are several lines of evidence against this hypothesis. The eucrite is sometimes shattered to a greater degree than some altered cone-sheets without showing replacement of pyroxene by hornblende. Thin-sections of eucrite sometimes exhibit lines of granulation crossing the pyroxenes, which show no alteration. Strong evidence was obtained by experimental determination of the relative permeabilities of the two rocks. A porphyritic cone-sheet in which the pyroxene was largely unaltered was collected 1,500 yards east of Slieve Foye summit. A representative massive unfractured eucrite specimen, in contact with a porphyritic cone-sheet in which the pyroxene was mostly replaced by hornblende, was taken from a place about 800 yards north of Slieve Foye summit. Both specimens were cleaned with a wire brush and weighed. They were then placed in a closed steel cylinder from which the air was exhausted by a vacuum pump. Water was then introduced into the cylinder under a hydrostatic head of sixteen feet. After several days the specimens were taken out and the excess water was carefully removed from their surfaces. The specimens were weighed again. The results are tabulated below:—

	Eucrite	Porphyritic cone-sheet
Weight after soaking in water	152·160 grams	106·443 grams
Weight of specimen dry	151·690 „	106·230 „
Gain	000·470 „	000·213 „
Gain %	0·3%	0·2%

These figures suggest that the eucrite actually would be more permeable than the cone-sheets to the passage of migrant solutions from the granophyre.

It can be concluded, therefore, that at certain temperatures and hydrostatic pressures the pyroxene of the eucrite was stable in comparison with that of the porphyritic cone-sheets and that in the disintegration of the latter heat was the essential factor. The two pyroxenes have the same type of silicate lattice so that the only explanation of their different stabilities must lie in their chemical compositions.

The important chemical differences between the pyroxenes appear to be as follows. Compared with the cone-sheet pyroxene that of the eucrite shows values much closer to unity for the X and Y groups (X 0·839, Y 1·174). In the cone-sheet pyroxene (X = 0·663, Y = 1·314) decrease in the X group value is entirely at the expense of calcium, since values for sodium and potassium, although low, are higher than in the eucrite pyroxene. In the enlarged Y group Fe″ is much more abundant than in the pyroxene from the eucrite. All these relationships may be taken to indicate that much calcium is replaced by Fe″ in the cone-sheet pyroxene but not in the eucrite pyroxene. There is a good deal of difference between the ionic radii of Ca″ and Fe″ and, as pointed out by Edwards (1942, p. 598) the replacement of a large calcium ion by a small ferrous ion involves considerable distortion of the lattice. Edwards presents much evidence for the reality of this replacement in clinopyroxenes from basic igneous rocks and argues that with moderately slow cooling there must be a limit to the replacement; beyond this limit (about 25–30% $CaSiO_3$, when $CaSiO_3 + MgSiO_3 + FeSiO_3 = 100$) the augite lattice becomes unstable (Edwards, 1942, p. 601). This value is approached by the cone-sheet pyroxene ($CaSiO_3$ about 35% in Edwards' diagram).

Muir (1951) in a detailed account of the clinopyroxenes of the Skaergaard intrusion shows that in the clinopyroxenes of the later middle gabbros X decreases notably and Fe″ replaces Ca″ up to a limit beyond which the lattice would become unstable. The chemical composition of the Skaergaard pyroxene nearest this limit (FeO 17·56% MgO 11·63% CaO 14·12%) is not greatly dissimilar to that of the Carlingford cone-sheets. Whilst the pyroxene of the Carlingford eucrite is comparable with the early diopsidic varieties from Skaergaard. It seems therefore reasonable to conclude that the relative instability of the cone-sheet pyroxene may be partly explained by extensive replacement of Ca″ by Fe″ straining the lattice.

From the papers just quoted and numerous others in the literature a further point can be made. Frequently it is shown that the earliest clinopyroxenes to separate from a basic magma are diopsidic, whilst later clinopyroxenes become enriched in iron at the expense of calcium and magnesium. The pyroxene of the Carlingford eucrite compares with the early pyroxenes, the cone-sheet pyroxene compares with the later pyroxenes. The cone-sheets and eucrite belong to one igneous

complex and the cone-sheets cut the eucrite. The pyroxenes of the two rocks may therefore possibly represent a pyroxene trend of crystallization, the eucrite pyroxene being the earliest member. This being so it is interesting that the cone-sheet pyroxene was the first to be affected by thermal metamorphism for it commonly happens that in progressive thermal metamorphism the minerals of basic igneous rocks are affected in the reverse order of their magmatic crystallization (Harker, 1939, p. 109). It seems most likely that some such effect has expressed itself in the different stabilities of the two pyroxenes described. In this case, however, two members of one isomorphous series are involved, not, as Harker apparently only had in mind, members of different mineral groups.

ACKNOWLEDGMENTS

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CORRESPONDENCE

"HUTTON'S UNCONFORMITY"

SIR,—I have read with interest Dr. S. I. Tomkeieff's careful re-description of "Hutton's Unconformity", Isle of Arran.

It is to be regretted, however, that Dr. Tomkeieff has overlooked, no doubt inadvertently, the section of the unconformity which the writer published in 1944, as part of a general account of the Dalradian rocks of Arran.

It was then made clear that the unconformity does, in fact, lie in the position in which it is shown by Dr. Tomkeieff and that underneath the unconformity there are four feet of calcitized grit forming part of the Dalradian schists.

That Geikie's interpretation of Hutton's description required this modification has, indeed, been known to the author since 1939, and has been accepted by several parties who have visited Arran since the publication of the writer's paper. Further references to this paper were given by the writer in 1947, and by Dr. J. E. Richey in 1948.

J. G. C. ANDERSON.

UNIVERSITY COLLEGE,
NEWPORT ROAD,
CARDIFF.
11th December, 1953.

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REVIEWS

GEOLOGIE DER SCHWEIZER ALPEN. By J. CADISCH (2nd ed.). pp. x + 480, with 59 figs. and 2 plates. Wepf and Co., Basle, 1953. SFr. 42·30 (approx. 75*s.*).

Since Heim's monumental volumes, the first edition of this treatise by Cadisch has been the principal alternative general description of the geology of Switzerland; both these have now been out of print for some time so that the appearance of a substantial modern work is much needed.

The pattern of the second edition continues essentially as before with much revision, new material, and a hundred extra pages. After an introduction to the tectonic ideas involved, Part II is a study of the igneous, metamorphic, and sedimentary rocks and processes. The first two of these are now written and expanded with petrogenetic emphasis by E. Niggli. Then Cadisch, after discussing general aspects of sedimentation and climates, treats the stratigraphy of each of the principal tectonic groups. This comprises more than a quarter of the book and within each tectonic group there is a systematic description of the stratigraphy, and many successions within individual nappes are represented in tabular form. Part II concludes with some pages on the mode of formation of the Alps which with the introduction will be the most interesting general reading. We find here, for instance, that the Jura mountains have for some time been assumed to be deeply folded. In these few pages many aspects of Alpine theory are summarized.

Part III is a survey of the Alps in nine regions (Niggli writing on the Gotthard and Tavetch Massifs). Most of these are sectors taken from west to east and bounded by the main rivers cutting across the strike of the Alps. The principal structural features are outlined and illustrated by tables, diagrammatic sections, and sketch maps. Without access to the excellent sheets of the official atlas and special sheets with tectonic *préçis* insets the foreign reader will find himself wishing for folding maps illustrating most of the structures and places referred to in the book. Perhaps, however, the chief value of this part is not so much as a detailed guide to the ground but rather to the latest research on the region with ample references to recent publications. This is conveniently followed by a bibliography including most original work published since 1920. Finally there is an index of place-names. There is a very full table of contents at the beginning but no other

index. The diagrams are adequate but not extravagant and half-tone illustrations are collected at the end out of their numerical order with the text-figures. They are in excellent company with the author's well-known "Tektonogramm" of the whole Swiss Alps.

The treatise is logically constructed, clearly written, and attractively printed; and it provides a systematic account without parallel to-day. British geologists who have used the earlier edition will find this a worthy successor. Those who have been content to master the Alps from the three or four works in English would do well to check here before committing their generalizations to print, for while such works may well continue to introduce the English-speaking geologist to the Alps, Cadisch fulfils for us the complementary function of a reliable and up-to-date work of reference.

W. B. H.

GEOLOGY OF AUSTRALIAN ORE DEPOSITS. A Symposium. Edited by A. B. EDWARDS. pp. xiv + 1,290, with 4 plates and 425 text-figures. Australasian Institute of Mining and Metallurgy. Melbourne, 1953. Price £5.

This *magnum opus*, a worthy successor to the Canadian Institute of Mining and Metallurgy's Jubilee Volume on the *Structural Geology of Canadian Ore Deposits*, epitomizes the geology of practically all the important metalliferous deposits in Australia, including those now being worked and many which have been exhausted or abandoned. The volume opens with two informative chapters, one on the mineral production and resources of the continent, and the other on the tectonic setting of the ore deposits and their relationship to rock folding, fractures, igneous action, favourable beds, and erosion. These are followed by eleven chapters, each comprising an introductory section on the relation between geological structure and mineralization throughout a particular region, which serves as a prelude to detailed descriptions of individual mines and mining fields in that region. Special emphasis is laid on the factors that controlled ore deposition, and in some cases the mineralogy of the ores is discussed at length.

It is significant that although many of the mineral deposits are clearly related genetically to certain igneous rock masses, several of the richest ore-bodies, including those of the famous Kalgoorlie, Mount Isa, Broken Hill, and Bendigo fields, lie in areas remote from possible parental igneous sources. In these circumstances it is not surprising that speculation is still rife concerning the source of the metals, some authors advocating a magmatic derivation whilst others invoke the transfusion and granitization of country-rocks containing traces of the ore-forming elements. It is a sign of the times that although there is unanimous agreement as to the importance of structural control in the localization of the great Broken Hill lodes, the long-held belief that the sulphides were transported upwards by hydrothermal solutions of igneous affiliation is now vigorously opposed by those who visualize migration of the ore minerals to their present site during the plastic deformation, metamorphism, and migmatization of lead- and zinc-bearing sediments.

No less than seventy authors have shared in the total of 135 articles, most of which close with a useful list of references. This volume, the first of eight published in connection with the Fifth Empire Mining and Metallurgical Congress held in Australia and New Zealand in 1953, gathers together a wealth of factual information and much stimulating discussion on ore deposits about which comparatively little has been recorded outside Australian literature. All concerned with its preparation, and especially the Editor, deserve praise for a meritorious achievement.

D. W.

PUBLICATIONS RECEIVED

Geology of the Country between Bradford and Skipton, by J. V. STEPHENS, G. H. MITCHELL, and W. EDWARDS, with contributions by C. J. STUBBLEFIELD and K. C. DUNHAM. pp. vii + 180, with 25 text-figures and 9 plates. *Geological Survey of Great Britain*, H.M. Stationery Office, 1953, price 25*s*.

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Summary of Progress of the Geological Survey of Great Britain and the Museum of Practical Geology for the Year 1952. pp. iv + 72. H.M. Stationery Office, 1953, price 2*s*. 6*d*.

Geological Survey and Museum. Classified Geological Photographs. 125 pp. H.M. Stationery Office, 1952, price 3*s*. 6*d*.

The Literature of Geology. Compiled by BRIAN MASON. Amer. Mus. Nat. Hist. (New York, 24), lithoprinted, 1953, 155 pp., price $2 post free. (Provides references to the most significant literature on the geology of individual countries, preceded by a general section containing abstracts, dictionaries, glossaries, and selected references in specific fields, e.g. stratigraphy, palaeontology, petrology, etc.)

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LAPWORTH, C. 1878. The Moffat Series. *Quart. Journ. Geol. Soc.*, xxxiv, 240–343.

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